Petrological and geochemical comparison of the ultramafic rocks of Tulppio, Jänesselkä and Värriöjoki, eastern Finnish Lapland

M.Sc. Thesis

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Tiivistelmä/Referat – Abstract

Komatiites are extrusive rocks crystallized from mantle derived high-MgO magmas. They formed mainly during the Archean as the required high degree partial melting of the mantle peridotite (>20%) was facilitated by the geotherm of that time. Komatiites are classified as volcanic rocks with >18 wt.% MgO and <1 wt. % TiO_2. By their physical features komatiite melts are of high-temperature and low-viscosity.

Komatiitic rock suites are abundant in the Archean bedrock of the eastern Finnish Lapland. They are mainly found as cumulate bodies with also their related komatiitic basalts and mafic volcanic rocks being abundant in the Tulppio Metavolcanic belt. Typical of Archean terrains in Fennoscandia, all komatiitic rocks in the eastern Lapland are extensively deformed and primary mineral assemblages and textures are rare. Mapping and sampling was performed in the municipalities of Savukoski and Salla, NE Finland, in order to clarify the geochemical characteristics and petrogenesis of the komatiitic suites of the Eastern Lapland Archean Domain (ELAD). On the basis of their lithology and previous studies, three komatiitic cumulate complexes were selected for detailed geochemical and petrographical comparison. These are the Jänesselkä mafic-ultramafic complex, the Tulppio ultramafic complex, also referred to as the Tulppio dunite, and the Värriöjoki ultramafic complex. The first two are situated in the Tulppio metavolcanic belt whereas the Tuntsa metasedimentary belt hosts the Värriöjoki ultramafic complex.

The lithology and geochemical characteristics of the Jänesselkä mafic-ultramafic complex suggest it having a different origin than the komatiitic rocks forming the Tulppio metavolcanic belt. Based on parental magma calculation and near continuum of rock types observed the Jänesselkä mafic-ultramafic complex represents a fractionated magma chamber with a basaltic composition (~6 wt. % MgO). The dunitic Värriöjoki ultramafic-complex is a feeder cumulate formed from a magma with a composition of high-MgO basalt (~12 wt. % MgO). Due to the similarities in their major- and trace element contents and suggested ages (2.45 Ga), the possibility of Värriöjoki and Jänesselkä being Paleoproterozoic suites with a similar primary magma is notable. Therefore, a petrogenetic link to the widespread 2.4–2.5 Ga mafic-ultramafic magmatism in the NE parts of the Fennoscandian shield, is proposed. The Tulppio ultramafic complex shows geochemical features suggesting a different origin in comparison to the two other complexes studies. Estimates on the parental magma composition (~17 wt. % MgO) and near chondritic REE contents suggest Tulppio being a feeder cumulate of earlier, possibly Archean magmatism in the area.

Owing mainly to the poor level of exposure and heavy post magmatic modification, any detailed interpretations on the origin of the target complexes are rather difficult to. Therefore, isotope studies are seen as a necessity to clarify these topics.

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Tiivistelmä/Referat – Abstract

Komatiitit ovat ultramafisista, vaippaperäisistä MgO-rikkaista magmoista syntyneitä kiviä. Niiden synty rajoittuu lähes yksinomaan arkeeisille ajoille, korkean vaipan sulamisen asteen (>20 %) olleen mahdollista sen aikaisen geotermin myötä. Kivilajina komatiitit määritellään vulkaanisiksi kiviksi, joiden MgO-pitoisuus on >18 % ja TiO_2-pitoisuus on <1 %. Komatiittisilla sulilla on korkea lämpötila ja hyvin matala viskositeetti.

Komatiittiset kivet ovat yleisiä Itä-Lapin arkeeisessa kallioperässä. Niitä tavataan yksittäisinä, usein koostumuksellisesti homogeenisina kumulaattiyksikköinä granitoidisessa kallioperässä sekä lähes jatkuvina koostumuksellisina sarjoina (MgO), kumulaateista laavoihin, Tulppion vihreäkivijaksossa. Itä-Lapin kiville on tyypillistä korkea metamorfoosiaste, minkä vuoksi primäärit mineraaliseurueet sekä rakenteet ovat niissä harvinaisia. Savukosken ja Sallan kuntien alueella hiljattain suoritettujen kartoitusten ja näytteenoton tarkoituksena on ollut tarkentaa Itä-Lapin arkeeisen alueen ultramafisten kivien geokemiallisia tunnuspiirteitä sekä käsitystä niiden synnystä. Kolme komatiittista kumulaattiyksikköä valittiin tämän tutkimuksen kohteiksi niiden edustavan litologian sekä aikaisempien tutkimusten perusteella. Nämä ovat Jänesselän mafinen-ultramafinen kompleksi, Tulppion ultramafinen kompleksi, johon kirjallisuudessa viitataan myös nimellä Tulppion duniitti, sekä Värriöjoen ultramafinen kompleksi. Näistä kaksi ensimmäistä sijoittuvat Tulppion vihreäkivijaksolle, Värriöjoen ultramafisen kompleksin sijaitessa Tuntsan metasedimenttijaksolla.

Jänesselän mafinen-ultramafinen yksikkö tulkittiin kentällä havaittavan koostumuksellisen vaihettumisen sekä kantamagmalaskujen perusteella syntyneeksi itsenäisesti magmasäiliössä fraktioituneesta basalttisesta (~6 MgO p. %) magmasta. Duniittinen Värriöjoen ultramafinen kompleksi tulkittiin MgO-rikkaiden (~12 MgO p. %) magmojen tulokanavakumulaatiksi. Näiden kahden yksikön välillä havaittavat geokemialliset samankaltaisuudet sekä arviot niiden i'istä (2,45 Ga) viittaavat Jänesselän mafisen-ultramafisen- sekä Värriöjoen ultramafisen kompleksien syntyneen samankaltaisista primäärimagmoista. Yhteys Fennoskandian kilven alueella paleoproterotsooisena aikana laajalti vaikuttaneeseen mafiseen-ultramafiseen magmatismiin on siis mahdollinen. Tulppion ultramafinen kompleksin geokemia viittaa sen alkuperän poikkeavan Jänesselästä ja Värriöjoesta. Arvioit Tulppion kantamagmasta (~17 p. % MgO) sekä lähes kondriittiset REE-pitoisuudet ovat vanhempaan, arkeeiseen magmatismiin sopivia piirteitä. Tulppion duniittinen yksikkö on mitä todennäköisemmin MgO-rikkaista magmoista syntynyt tulokanavakumulaatti.

Huonojen paljastumaolosuhteiden ja korkean metamorfoosin vuoksi tarkkojen tulkintojen tekeminen Itä-Lapin komatiittisten kumulaattien synnystä on vaikeaa. Näin isotooppitutkimuksia voidaan pitää välttämättöminä perusteellisemman petrogeneettisen mallin muodostamiseksi.

Avainsanat – Nyckelord – Keywords
komatiitti, kumulaatti, petrologia, geokemia, Itä-Lapin arkeeinen vyöhyke, prekambri, Savukoski, Salla

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1 INTRODUCTION

The bedrock of Finland hosts of multiple Archean and Paleoproterozoic greenstone terrains. These provide an excellent retrospect to the major tectonic and magmatic events that formed our Precambrian bedrock. Ultramafic volcanic rocks are representatives of high-degree melting events of the Earth's mantle (Herzberg, 1992; Arndt et al., 2008). The study of komatiites, the hottest lavas erupted on Earth, have an important role in understanding the thermal and chemical evolution of the mantle. Additionally, being carriers of base and precious metals, komatiites are economically important.

Albeit komatiites in eastern Lapland have been studied by Outokumpu Oy, the Geological Survey of Finland and Finnish universities during the past five decades, understanding of their nature and origin is rather vague, and no comprehensive knowledge of the regional geology has been gained. This is mostly due to poor accessibility of the vast wilderness areas. However, during the past two decades, modern geophysical data and more comprehensive road network have made the recognition of ultramafic rock suites easier and have enabled more detailed understanding of the geology of eastern Lapland.

Study of komatiitic cumulates formed at and proximal to ancient eruptive vents can play an important role in the attainment of a more detailed picture about the nature of mafic-ultramafic magmatism in eastern Lapland. Several large ultramafic cumulate bodies have been identified in eastern Lapland, from which three have been selected as targets of this study: the ultramafic complexes of Jänesselkä, Tulppio and Värriöjoki. Jänesselkä is actually considered as a mafic-ultramafic complex, as associated mafic rocks are abundant there.

The questions addressed in this thesis are: (a) what are the geochemical characteristics of these three complexes, (b) do the complexes represent the same magmatic event and (c) why are the ultramafic rocks of Jänesselkä mafic-ultramafic complex different from the other ultramafic rocks in eastern Lapland? These topics are considered through field observations and petrographical, geochemical, and mineral chemical examinations.

This thesis is part of a collaborative research project by the Geological Survey of Finland and the University of Helsinki: 'Modeling of Ni-(Cu-PGE)-bearing mineral systems; the origin, exploration potential, and metallogeny of ultramafic volcanic suites of eastern Lapland.' (Haapala et al., 2018).

2 KOMATIITES

On the basis of their physical and chemical characteristics, komatiites represent an extreme end-member of volcanism. Komatiitic melts formed almost exclusively during the Archean through high-degree partial melting of the mantle (Herzberg, 1992). Komatiitic lavas are hot (1400 to ~1600 C°) and low in viscosity (0.1 to 10 Pa s) (Huppert and Sparks 1985; Herzberg, 1992), with high MgO, Ni and Cr and low TiO_2 and Al_2O_3 contents (Arndt et al., 2008). Their extraordinary physical features have resulted in the formation of characteristic textures, the spinifex texture as the most prominent of them (Arndt et al., 2008). Their importance in metallogeny is also notable as komatiites are a source for many base and precious metals.

Komatiites are defined as volcanic rocks containing more than 18 % MgO, less than 1 % TiO_2, and less than 2 % of total alkalis (Le Bas, 2000; Arndt et al., 2008) (Figure 2.1). Chemically similar rocks with higher TiO_2 contents are meimechites. Ultramafic volcanic rocks that are associated with komatiites but contain less than 18 % MgO are komatiitic basalts. In non-komatiitic systems, these rocks are classified as picrites (Le Bas, 2000). Some authors (Kerr & Arndt, 2001; Arndt et al., 2008) consider the term komatiite to refer to only such komatiitic rocks that show the spinifex texture. In this thesis, the concept of komatiite is based on geochemical composition only, regardless of the mineral assemblage and texture of the rock.

Komatiites are found on every continent except Antarctica and are present in most of the Archean and some of the Paleoproterozoic greenstone belts. Some of the classic komatiite suites include: the type locality of komatiites in Barberton greenstone belt in South Africa (Viljoen & Viljoen, 1969), Abitibi greenstone belt in Canada (Pyke et al., 1973), Kambalda greenstone belt in Australia (Gresham & Loftus-Hills, 1981), and komatiites in the Fennoscandian greenstone belts (Makkonen et al., 2017). Some of the latter are Paleoproterozoic in age (Hanski et al., 2001).

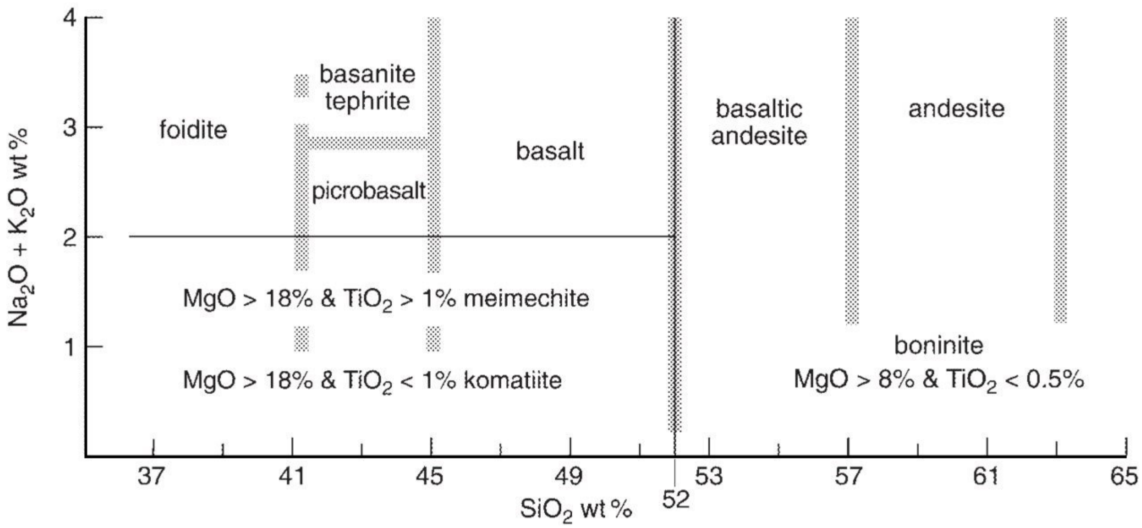

Figure 2.1: Classification of nomenclature 'High-Mg' volcanic rocks according to Le Bas (2000).

2.1 Structures and textures

The unusual physical properties of komatiite lavas have led to formation of some rather unique textures and structures. Low-viscosity of the lavas allow them to erupt and flow rapidly (Hubbert & Sparks, 1985) and also promote prompt settling of olivine and clinopyroxene phenocrysts to the base of the flows (Arndt et al., 2008). Large intervals in liquidus temperatures for silicate minerals in komatiite lavas are also a significant factor in formation of often layered komatiite structures. Whereas olivine is at liquidus at the eruption temperatures, usually around 1600 C°, the second liquidus phase, clinopyroxene appears only at 1200 C°. Thus, formation of different textures and structures is strongly dependent on the thickness of the flow, which mainly corresponds to vent distance (Hill et al., 1995).

Komatiite flows can have dimensions from dozens of centimeters thick and several meters wide to over 500 m thick and dozens of kilometers wide, with length up to several hundred kilometers (Hill, 2001; Arndt et al., 2008) (Figure 2.3). Classification of komatiitic flow types by Barnes (2006) shows the komatiite sequence with division to major magma pathways and compound flow fields (Figure 2.2). These include multiple different flow types with characteristic rock type, structures and textures. The end-members of these flow types are undifferentiated and differentiated flows (Hill et al., 1995). The first are usually thick flows and dominated by olivine cumulates formed by flow-through of large volumes of melt.

Whereas formation of layered structures in thick komatiite flow units is rare, in thin, less than 10 m thick units it is often explicit (Pyke et al., 1973; Arndt et al., 2008). In a well differentiated flow unit, the upper, spinifex textured unit is on top of an olivine cumulate unit underneath. In the undifferentiated end-member of the thin flow types, massive olivine unit often has a polyhedral jointing. The thin flows are often stacked and may form a succession of tens of flow units. Margins of the units are characterized by chilled and fractured flow tops (Pyke et al., 1973). The discussed end-members of flow types are not commonly seen in nature in comparison to more complex flow types presented in the figures 2.2 and 2.3.

Dunitic lenses and sheets, up to several kilometers thick, are often found in komatiitic sequences (Hill et al., 2004; Arndt et al., 2008). These are usually formed at and proximal to the eruptional vent with large amount of magma being passed through the system. Dunitic bodies of these types are common hosts for Ni-(Cu-PGE) deposits (e.g., Konnunaho, 2016 and references therein).

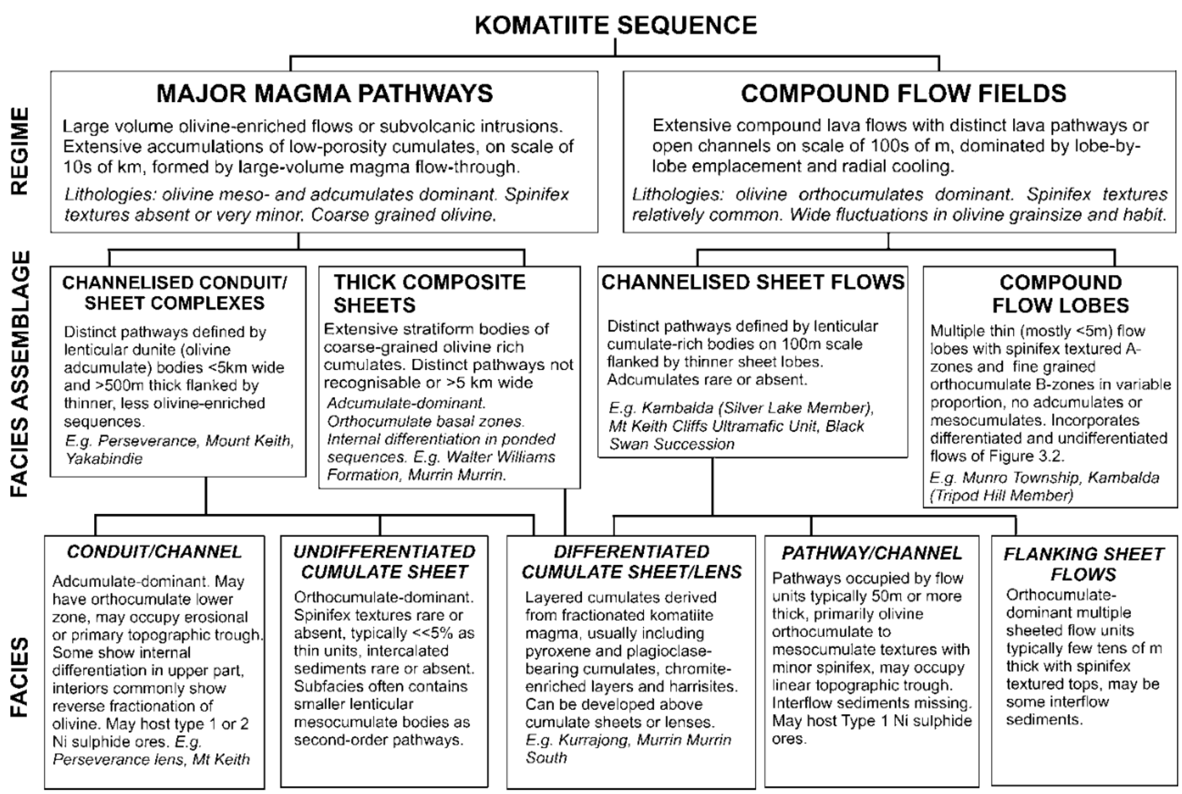

Figure 2.2: Classification of komatiite flow types (Barnes, 2006).

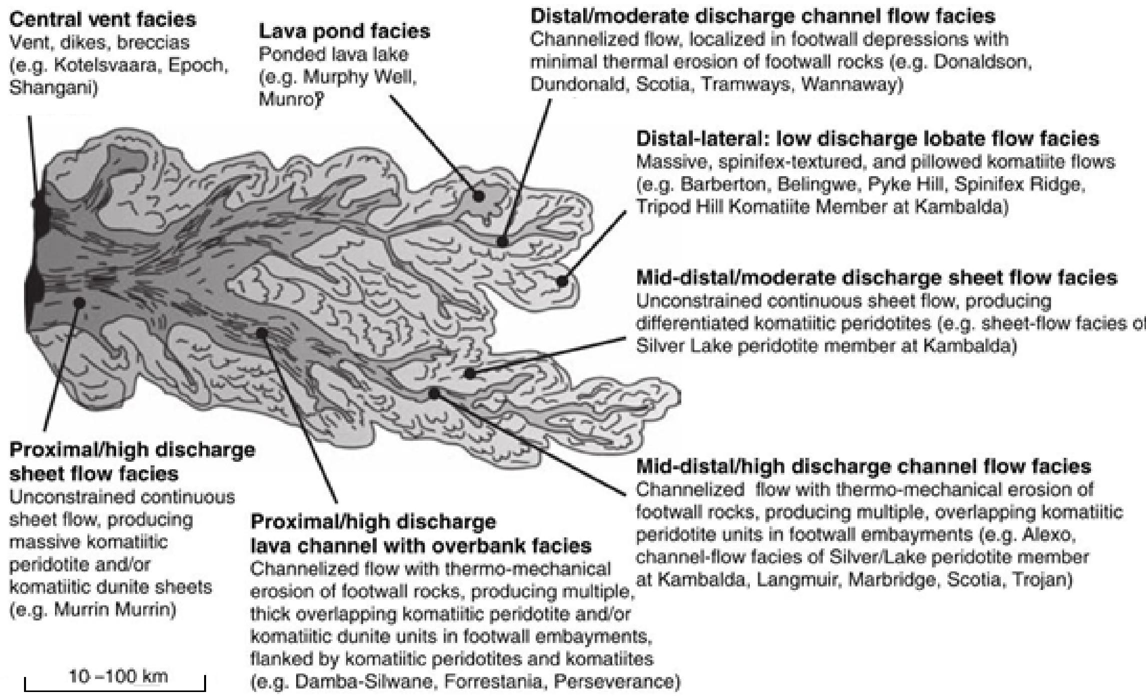

Figure 2.3: Schematic illustration of komatiite flow field with multiple different flow facies types and their relations to each other, modified after Hill et al. (1995).

2.1.1 Spinifex texture

First described from the Barberton greenstone belt by Viljoen & Viljoen (1969) and later named after a type of grass common in western Australia (Nesbitt, 1971), the spinifex texture (Figure 2.4) is the most famous of komatiite-related textures. Definition of spinifex texture (Arndt et al., 2008) comprises large, skeletal, and platy blades of olivine or acicular needles of pyroxene, in the upper parts of komatiite flows. In the classic spinifex layer of a komatiite flow, these are randomly oriented in the upper part and become platy and roughly parallel towards the base of the layer. In the case of platy olivine spinifex texture, typical interstitial minerals are pyroxene, chromite, altered glass, and in some cases plagioclase. In pyroxene spinifex texture, matrix composes of finer augite needles and glass or augite, plagioclase and lesser amounts of amphibole, quartz, ilmenite, and magnetite. Spinifex textured komatiitic rocks commonly represent the distal and lateral flows in the komatiitic flow fields (Figure 2.3)

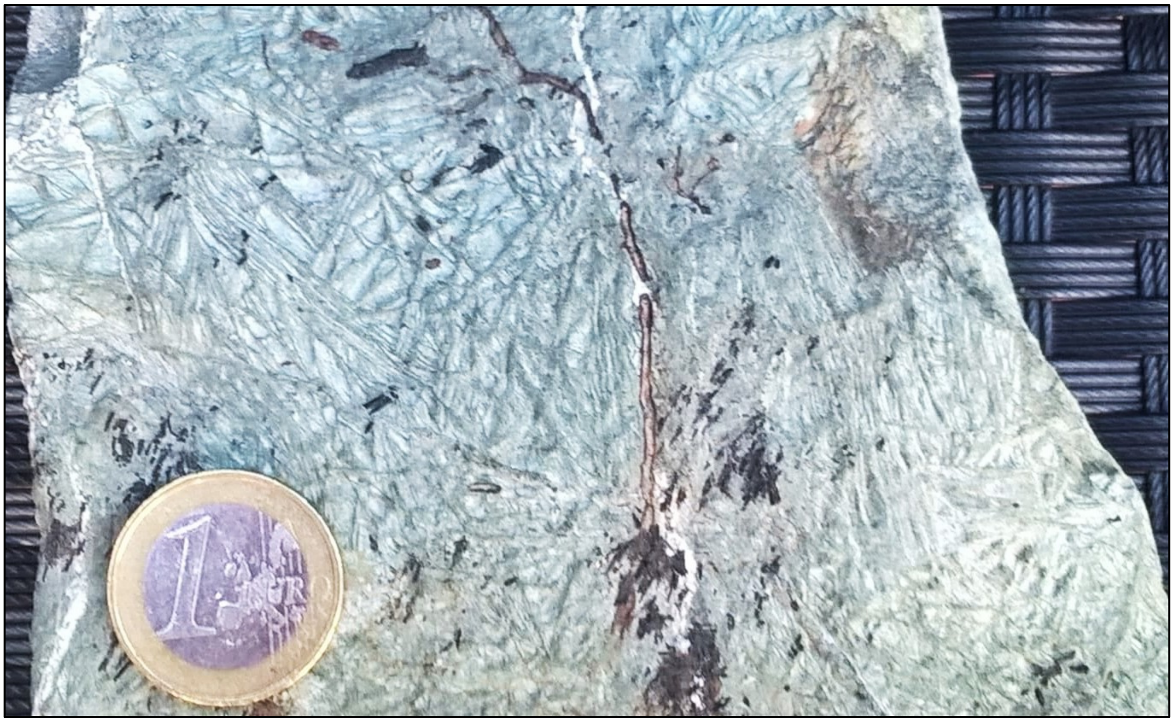

Figure 2.4: Relict randomly oriented pyroxene spinifex texture in a metamorphosed komatiite from Pahakangas, Kuhmo greenstone belt, eastern Finland. Coin diameter is 23mm. Photo by Tapio Halkoaho.

Spinifex texture in considered to form during relatively rapid crystallization of ultramafic magma (Pyke et al., 1973; Nesbitt et al., 1979; Arndt et al., 2008). It has been difficult however, to form a comprehensive model for the origin of spinifex texture, especially considering the cooling rate of the magma. It has been estimated that after the rapid crystallization of the uppermost layer of a (typically 5–10 m thick) submarine komatiitic flow, the interior cools at the rate of 1 C°/h (Donaldson, 1982). In laboratory, reproduction of platy spinifex olivine crystals requires a cooling rate of > 50 C°/h (Donaldson, 1982). Attempts to solve this problem include concepts of differences in MgO contents in komatiitic magmas and experimental charges (Donaldson, 1982), rapid cooling of the interior by vigorous convection of the komatiite flow (Turner et al., 1986), accompanied by hydrothermal circulation through the upper crust zone of the flow and radiative heat conduction (Shore & Fowler, 1999). None of these is seen as an all-encompassing model for the formation of the spinifex texture. However, a strong thermal gradient in the cooling komatiite flow seems to make the dendritic growth of olivine crystals possible, regardless of the cooling rate of the magma (Faure et al., 2006).

2.1.2 Harrisite texture

With some similarities to the platy spinifex texture, the harrisite texture is characterized by very large, often tens of centimeters long, branching olivine crystal with a crude skeletal habit (Arndt et al., 2008). This texture is typically related to basal parts of komatiitic bodies at shallow depths, where it forms to the basins of magma flows through olivine supersaturation. This is a consequence of supercooling of the komatiite magma (Donaldson, 1982). In contrast to harrisite texture that shows randomly oriented olivine grains and has formed in the accumulating grain mush, upwardly reaching, more parallel, tongue-like grains form at the mush-melt boundary instead (Donaldson, 1982). This latter case is related to ponding of intercumulus melt, in which case crystal growth is accelerated towards the crystal free liquid at the magma-mush boundary.

2.1.3 Cumulate textures

Cumulate terminology by Wager et al., (1960) may be used when considering komatiitic cumulates. This classification presents the terms ortho-, meso-, and adcumulate for cumulate rocks, depending on the amount of cumulus minerals in relation to intercumulus material: prefix "orto" for 50 – 75 %, "meso" for 75–95 %, and "ad" in case of >95 % of cumulus material. For komatiites, the term adcumulate is used for rocks with over 93 % of cumulus minerals.

In a fully developed komatiite flow (Figure 2.5), the spinifex layer is underlain by cumulates (Pyke et al., 1973). These are usually olivine orthocumulates with decreasing amount of intercumulus material towards the base of the flow. Intercumulus phases are pyroxene and glass. Cumulus olivine grains are dominantly subhedral and equant to tabular (Arndt et al., 2008). In the case of a pyroxenitic bulk composition, pyroxene cumulates are often found as a discrete layer on olivine cumulates that may be overlain by a gabbroic layer (Donaldson, 1982).

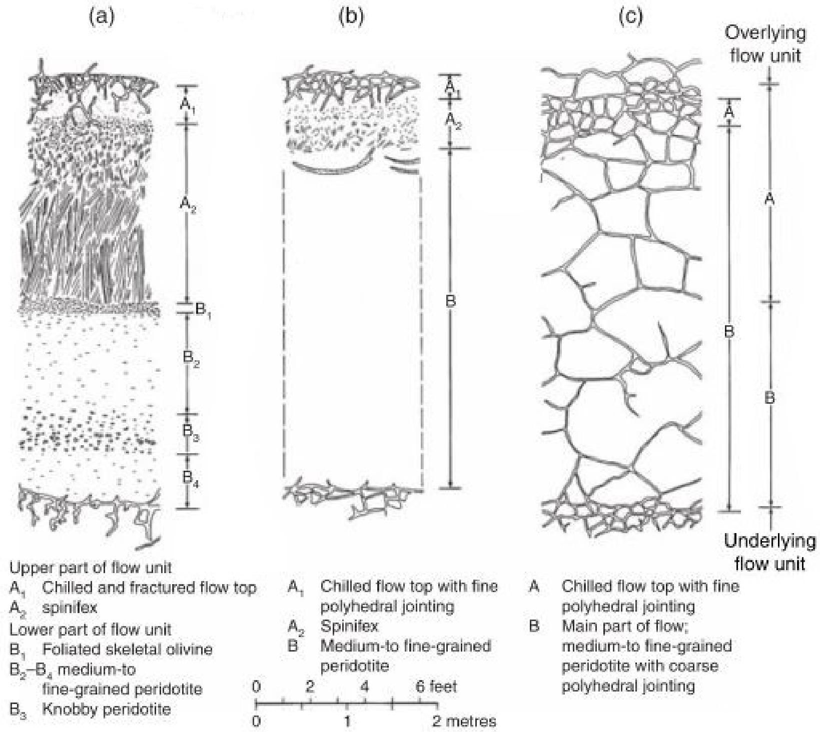

Figure 2.5: Types of thin komatiite flows, from Pyke et al. (1973): (a) completely differentiated flow with spinifex-textured upper part and olivine cumulate lower part; (b) partially differentiated flow with thin spinifex-textured layer and olivine cumulate lower part; (c) undifferentiated polyhedrally jointed massive flow.

Komatiitic sequences often include dunitic ad- and mesocumulates. These bodies may have dimensions of several kilometers (Hill et al., 2004). Olivine adcumulates of komatiitic sequences are a product of high volume flow-through of magma. Turbulent flow efficiently drains the intercumulus liquid as it is squeezed from between accumulating olivine grains. This process is also significant in the formation of cumulate layers in thinner flows (Arndt et al., 2008).

2.2 Mineralogy

Scarcity of magmatic, rock forming minerals is characteristic for komatiites. Usually komatiites have olivine, pyroxene and glass as main phases. Chromite is a common accessory mineral that, however, can be the only other major mineral along olivine in dunitic parts of komatiite sequence. Plagioclase and quartz may also be present in komatiites. These are not discussed in this section, as their contents are not significant in komatiites.

2.2.1 Olivine

Olivine in komatiites can have rather variable morphology. Donaldson (1982) described five main types of olivine crystals (Figure 2.6):

(1)'Hopper olivine': euhedral to subhedral, equant to elongate crystals with hollow, or embayed cores.

(2)'Plate olivine': tabular plates of blades of two or more olivine grains. These are stacked and parallel, or nearly parallel to one another. Often dendritic by shape.

(3)'Branching olivine': similar to 'plate olivine', with more divergent branches, that stem from multiple nucleation points.

(4)'Polyhedral olivine': euhedral crystals with equant to tabular shape. These crystals have no embayments.

(5)'Granular olivine': subspherical crystals.

These types are well represented in many well differentiated, spinifex-textured komatiites. Pyroxene, as a spinifex-texture forming mineral, can show similar crystal morphologies to olivine (Donaldson, 1982).

In general, magmatic olivine in komatiites is highly forsteritic and shows zoning with more fayalitic rims with relation to cores. Similar slight enrichment in Fe is common towards the top of the cumulate layers of differentiated komatiite flows (Donaldson, 1982). Generally, forsterite content of olivine in Archean komatiites ranges from Fo_{85} to Fo_{95} (Arndt & Nesbitt, 1982; Donaldson, 1982; Arndt et al., 2008). Highest magmatic forsterite contents reported ($Fo_{96.5}$) are from Barberton greenstone belt (Kareem & Byerly, 2003). Similar Mg-rich olivine is common in other Archean komatiite suites (Echeverria & Aitken, 1980; Arndt, 1986a). Olivine in Paleoproterozoic komatiites usually shows more Fe-rich composition (Hanski et al., 2001).

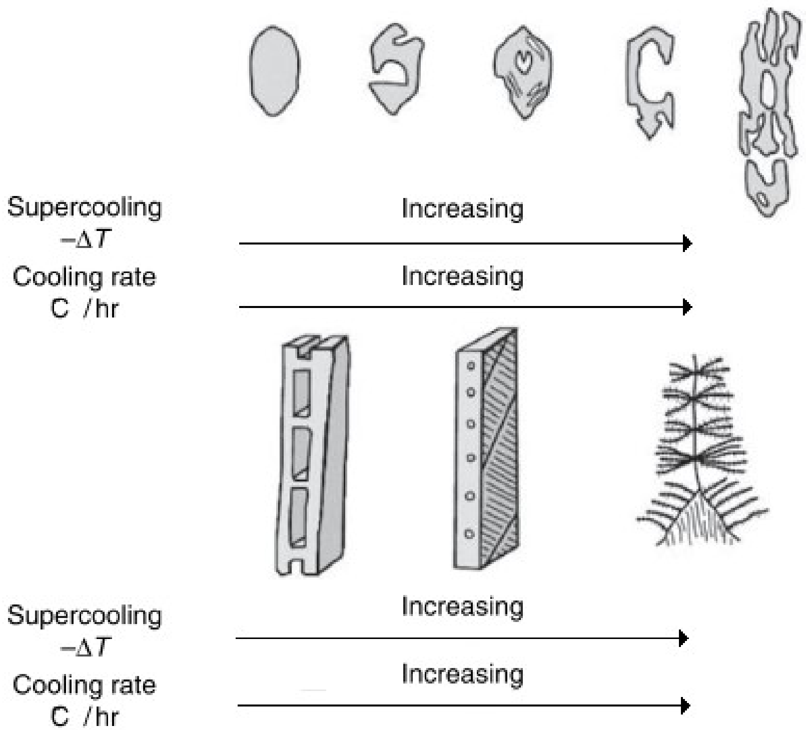

Figure 2.6: Olivine crystal morphology in komatiite associations relative to supercooling and cooling rate. Modified after Donaldson (1982). The morphologies from polyhedral olivines (top left) to hopper olivines (top right) are typical for olivine in the interior of a lava flow. Lower illustrations on morphologies are “chain”, “lattice”, and “feather” olivine. These are found at rapidly cooled chill margins of komatiite flows.

2.2.2 Pyroxenes

Typical pyroxenes in komatiites are augite and pigeonite (Arndt et al., 2008). These show varying morphologies depending on the composition of the host lava and the position of crystallization within the lava unit. Magmatic crystal types of pyroxenes observed are (Arndt et al., 2008): (a) large and composite megacrysts with elongate skeletal habit, main spinifex-texture forming pyroxene; (b) prismatic cumulus grains at the cumulus layers of the lava flows; (c) prismatic and small pyroxene needles with dendrites and feathery intergrowths. The latter are found in the matrix of spinifex, cumulate and porphyritic lavas.

The most impressive form of pyroxene is the composite crystals forming the pyroxene spinifex texture (Wilson & Carlson, 1989). These are usually highly complex and consist of pyroxene needles with individual needles having a pigeonite core and an augitic margin (Arndt et al., 2008). These grains often show step-like transition from high-Cr and high-Mg# pigeonite core to higher Al_2O_3 and CaO towards the augite rim. This zoning is interpreted to represent the crystal growth outwards from pigeonite core, starting point identified by the highest Cr content (Arndt & Fleet, 1979).

Orthopyroxene in komatiites is not common. However, in the relatively rare Si-Mg-rich komatiites it may appear as other pyroxene phase (Byerly, 1999). The presence of orthopyroxene in komatiites is usually related to SiO_2 input to magma through crustal contamination. This is a crucial process for formation of komatiite related ore deposits (Lesher & Groves, 1986).

Pyroxenes in cumulate and gabbroic layers in komatiites and komatiitic basalts have a composition similar to other mafic flows and intrusions, with augite and bronzite as the most common minerals (Arndt et al., 2008). Grains with prismatic, subhedral to euhedral habit are dominant.

2.2.3 Chromite

Chromite in komatiites is most abundant in differentiated layered cumulate bodies and least abundant in highly magnesian chromite-undersaturated lavas. Its crystal habit ranges from euhedral to skeletal depending on the composition and cooling regime of the co-existing olivine (Barnes, 1998). In spinifex lavas, chromite is usually found as dendritic skeletal grains. In spinifex cumulates and dunitic bodies these grains are more euhedral. In some rare instances, chromite is found as interstitial to poikilitic anhedral grains (Barnes & Hill, 1995; Telenvuo, 2017).

Lava composition and oxygen fugacity control the composition of precipitating chromite. Normally rocks in thick dunitic bodies show much lower Fe^{3+} contents in contrast to higher Fe^{3+} contents in differentiated layered komatiite flows (Barnes, 1998). This seems to be a consequence of highly reduced state of the magma, which later becomes oxidized during post-eruptional processes. Similar enrichment can usually be seen in the zoned nature of the grains, as the margins show higher Fe and Ti but lower Cr values than the cores (Arndt et al., 2008). This zoning intensifies in metamorphic processes, as sub-solidus re-equilibration with olivine usually leads to addition of Fe to the interstitial chromite (Barnes, 1998).

2.3 Geochemistry and classification

The primary chemical characteristics of komatiites are controlled by the degree of melting of mantle peridotite. The most distinguished feature is the high MgO content produced by high-degree partial melting of the mantle (Herzberg, 1992). In addition, komatiites are rich in other mantle-compatible elements such as Cr and Ni and poor in mantle-incompatible elements such as Al, Si and Ti. Besides the control by the degree of melting of the mantle, the major element content of the forming melts is affected by the composition of the melting mantle peridotite (McDonough & Sun, 1995), which may vary as a function of depth (Robin-Popieul et al., 2012) and the prevailing pressure during the melting (Herzberg, 1992). In comparison to other high-MgO rocks (e.g. meimechites), komatiites show lower concentrations of alkalis, P_2O_5, TiO_2, H_2O, and CO_2 (Arndt et al., 2008). Komatiites also show geochemical variation due to differentiation processes that took place after the formation of the primary melt(s) in the mantle. These are e.g. early crystallization of olivine that reduces the magma of MgO (Arndt, 1986b), magma mixing (Jellinek & Kerr, 1999), crustal contamination (Brand, 1999), and post magmatic modification (Gole et al., 1987). These processes can also cause significant changes to the trace element contents of the komatiites. Usually uncontaminated komatiites are depleted in incompatible trace elements, with depletion in LREE in relation to HREE being typical.

Komatiites can be divided into two groups on the basis of their degree of Al depletion: Al-depleted komatiites (ADKs) and Al-undepleted komatiites (AUKs) (Nesbitt et al., 1979). These two groups are also referred to as Barberton- (ADKs) and Munro-type (AUKs) (Arndt et al., 1977). ADKs are typified by Al_2O_3/TiO_2 values less than 15. These rocks usually have superchondritic Gd/Yb_n ratios (~1.3–1.6) (Sossi et al., 2016). AUKs, on the other hand, are defined as komatiites with Al_2O_3/TiO_2 ratios higher than 15. The third, but less common type, of Al-enriched komatiites (AEKs) has also been recognized in some komatiite suites (Jahn et al., 1982).

To eliminate the effects of differentiation, and to enhance the comparison of magmas with varying MgO contents, komatiites have also been classified by the degree of their Ti-enrichment (Hanski et al., 2001). This classification is shown in Figure 2.7, which illustrates mole proportions of Al_2O_3 and TiO_2 from projected magmatic olivine compositions. Major advantage of the diagram is that it distinguishes low-Ti komatiites from, high-Ti komatiites and picrites (Hanski et al., 2001; Arndt et al., 2008). The overabundance of TiO_2 is typical for Proterozoic komatiites and seen as a consequence of more TiO_2-rich mantle source (Hanski et al. 2001).

Pressure conditions of partial melting is the main controlling factor for the degree of Al depletion in the komatiite magmas (Nesbitt et al., 1979; Jahn et al., 1982; Nesbitt et al., 1982; Herzberg & O'Hara, 1998; Arndt et al., 2008). Formation of ADK magmas is explained by Al retention by garnet in high-pressure environments with garnet in the residual. AUK magmas would form in lower-, garnet-absent pressures. A single komatiitic magma source seems to have the possibility to produce both types of komatiites, however. This is explained by changes in the degree of melting across the axis of the mantle plume, where AUKs form in the hotter, axial parts and ADKs form in the cooler, distal parts (Sossi et al., 2016).

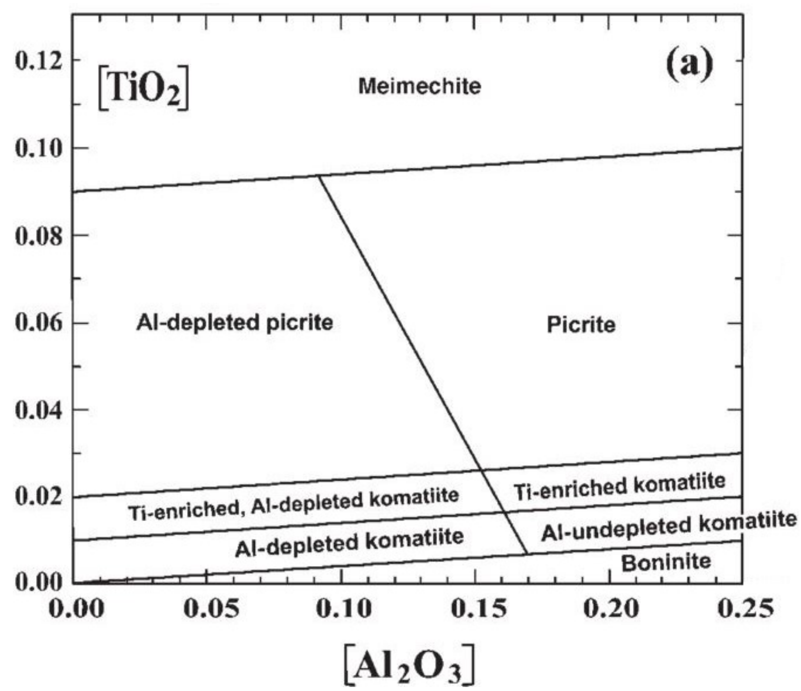

Figure 2.7: Classification of high-MgO volcanic rocks by Hanski et al. (2001).

2.4 Origin of komatiite melts

High temperature is the most profound factor for the formation of komatiitic melt in the mantle. As the primary magmas were anhydrous, it is unlikely that komatiites could have been formed in water-enriched sources like subcontinental lithospheric mantle, or the mantle wedge above subduction zone. This has led to a suggestion of mantle plumes being the most potential komatiite source (Nesbitt et al., 1979; Anderson, 1994; Arndt et al., 2008; Robin-Popieul et al., 2012). Contrary to prevailing petrogenetic models, significant role of water in the formation of komatiitic melts have been suggested by several authors (Stone et al., 1997; Wilson et al., 2003). These estimations about the Archean komatiitic melts containing up to 2 wt.% H_2O is seen problematic, however. This is due to lack of degassing textures in komatiites and the highly incompatible nature of H_2O, which should have led to early H_2O-depletion of mantle after its formation (Arndt et al., 1998).

Considering major elements, the source of the komatiites has been suggested to have had higher Mg/Fe and Fe than commonly suggested for the pyrolite composition (Francis, 1995). The proportions of eclogite and peridotite in the source have been estimated from the composition of olivine in komatiites (Sobolev et al., 2007). Based on these studies, the source for Archean komatiites contained approximately 20 % eclogite, whereas the Proterozoic mantle source contained 40 % of eclogite. Experimental studies support this estimate (Herzberg & O’Hara, 1998). On the basis of the trace element contents, the source of komatiitic melts would have been similar to primitive mantle (Palme & O’Neill, 2003).

3 KOMATIITIC ROCKS OF FINLAND

The Finnish bedrock includes both Archean and Proterozoic greenstone belts (Figure 3.1). Komatiites have been found in the Archean Tipasjärvi-Kuhmo-Suomussalmi greenstone belt in the eastern Finland (Piirainen, 1988; Luukkonen, 1992), Tulppio greenstone belt in eastern Lapland (Juopperi, 1994), and smaller Archean greenstone belts in Hattu in Ilomantsi terrain (O'Brien et al., 1993) and in Rommaeno Complex in NW Lapland (Konnunaho, 2016). Proterozoic greenstone belts include the Kuusamo-Salla greenstone belt in SE Lapland (Silvennoinen, 1972), the Pulju greenstone belt in northern Lapland (Hanski et al., 2000) and Kolari-Kittilä-Sodankylä greenstone belt (Hanski & Huhma, 2005) in central Lapland. Many of the komatiite suites mentioned above are hosts for komatiitic Ni-(Cu) deposits (Konnunaho, 2016).

Situated in the Karelian craton, Archean greenstone belts of eastern Finland form a 10-km-wide and a 200-km-long N-S oriented zone surrounded by tonalite-trondhjemite gneisses (Halkoaho et al., 2000; Papunen et al., 2009). The majority of ultramafic rocks have undergone extensive deformation. However, also primary textures, like spinifex are found at least in the youngest komatiites of the area. The first stratigraphic models from the area were mainly based on field studies and textures from the Siivikkovaara-Kellojärvi area, in which volcanic rocks and their primary structures are well preserved (Hanski, 1980). Recent geochronological studies from felsic to intermediate volcanic rocks associated with komatiites suggests four major magmatic events in forming the greenstone belts of Tipasjärvi-Kuhmo and Suomussalmi (Lehtonen et al., 2016; Lehtonen et al. 2017). The Suomussalmi greenstone belt hosts the oldest volcanic group (2.94 Ga), whereas the youngest volcanic phase (2.80–2.79 Ga) is represented in the Tipasjärvi-Kuhmo greenstone belt. Geochemical resemblance of Kuhmo komatiitic and basaltic rocks with modern oceanic plateau basalts suggests that these rocks were in an oceanic plateau setting (Hölttä et al., 2012; Nironen, 2017). Multiple Ni-(Cu-PGE) deposits are known from the Archean greenstone belts of eastern Finland; Vaara, Hietaharju, and Peura-aho in Suomussalmi greenstone belt being the ones with most economical potential (Konnunaho, 2016).

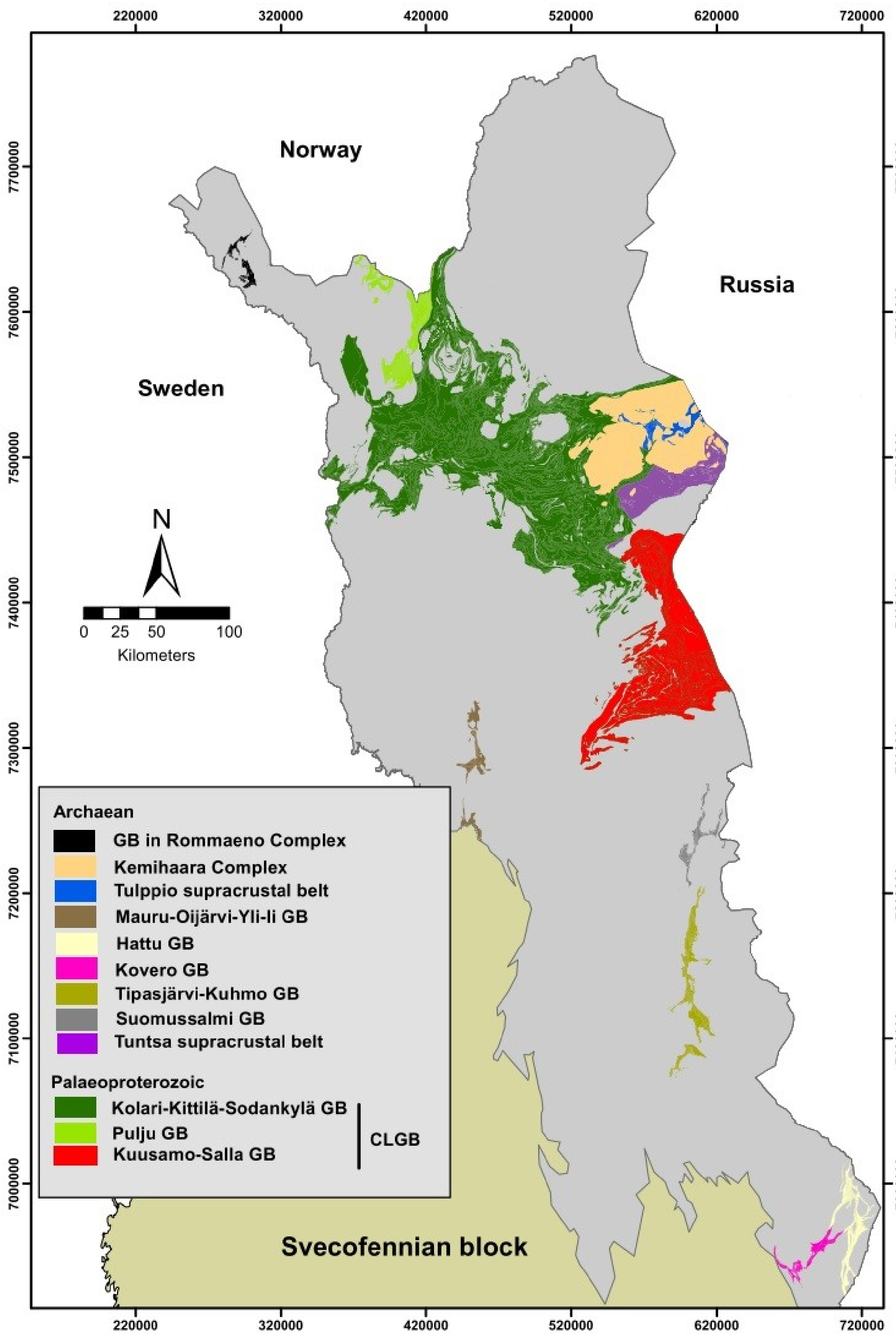

Figure 3.1: Greenstone belts and classical komatiite suites of Finland. Modified after Konnunaho (2016).

The Central Lapland greenstone belt (CLGB) consists of greenstone belts of Pulju, Kolari-Kittilä-Sodankylä and Kuusamo-Salla, and their continuations in Sweden, Norway, and Russia (Hanski & Huhma, 2005). Together, these form one of the largest known Paleoproterozoic greenstone belts. Proterozoic magmatism forming CLGB started as a consequence of a major extensional event at 2.45–2.43 Ga (Nironen, 2017). This earliest phase is represented by the majority of layered mafic intrusions in northern Finland and mafic-ultramafic volcanic rocks of the Salla-Kuusamo belt, the stratigraphically lowest Proterozoic group in CLGB stratigraphy. Komatiitic rocks of this group are restricted to upper part, also referred as the Onkamo group (Hanski & Huhma, 2005). These include komatiites in Mäntyvaara formation (Manninen, 1991), in the Salla area, and komatiitic basalts of the Möykkelmä dome (Räsänen et al., 1989) north of Sodankylä. The latter has been described as the type area of the Onkamo group. Komatiitic basalts of Möykkelmä form a 250 m thick series of varying compositions ranging from komatiitic basalt to andesite. These rocks show strong enrichment in LREE and a negative Ta anomaly, suggesting crustal contribution from Archean upper crust (Räsänen et al., 1989).

The metasedimentary rocks of the Sodankylä group are found on the metavolcanic rocks of the Salla-Kuusamo greenstone belt and are themselves overlain by the Savukoski group. Sodankylä and Savukoski groups contain komatiites in the CLGB (Hanski & Huhma, 2005). Ultramafic volcanic rocks of the Savukoski group are referred to as komatiite-picrite association as both compositions are widespread in the suite that extends from municipalities of Salla and Savukoski to the northern parts of Finnmark County in Norway. In Finland, komatiites of this association have been found in Sattasvaara, Kummitsoiva (Saverikko, 1985), Jeesiörova (Hanski & Huhma, 2005), and in Pulju greenstone belt (Konnunaho, 2016). Picrites have been described in Sotkaselkä (Lehtonen et al., 1998) and Peuramaa (Hanski & Huhma, 2005) areas. Volcanic rocks of the Savukoski group have been interpreted to be related to the attenuation and break-up of the Karelian craton at 2.1–2.05 Ga (Nironen, 2017; Huhma et al., 2018). Many mafic-ultramafic layered intrusions of northern Finland belong to this age group, Ni-ore-bearing Kevitsa (Mutanen & Huhma, 2001) as one of the most notable ones.

4 GEOLOGY OF THE STUDY AREA

The Eastern Lapland Archean Domain (ELAD) is located in the municipalities of Savukoski and Salla next to the Russian border of Finland. The area is approximately 6000 km^2 in size and is one of the least accessible regions in Finland. The first lithological maps of the ELAD were compiled by Mikkola (1941), followed by the more comprehensive work by Juopperi (1994). This chapter is based mainly on the geological description of Juopperi (1994) and geochronological work of Juopperi & Vaasjoki (2001).

4.1 Lithotectonic characteristics of the ELAD

Tectonically, the ELAD is the north-easternmost part of the Karelian province (Luukas et al., 2017) – the largest crustal province of the Fennoscandian shield. the ELAD is surrounded by the Lapland granulite belt in the north, The Central Lapland greenstone belt in the west and south and the Belomorian belt in the east. In some studies, the ELAD is considered as a part of the Belomorian belt (Gaal & Gorbatschev, 1987; Turchenko, 1992; Slabunov et al., 2006a), as it shows similar lithological traits in all parts of ELAD extending to the Beolomorian province on the Russian side of the border (Hölttä & Heilimo, 2017).

The geology of the ELAD is bimodal by nature, characterized by mostly tonalitic to granodioritic gneisses, mafic–ultramafic metavolcanic rocks, and metasedimentary rocks. Intermediate compositions are notably lacking (Kauniskangas, 1987; Sorjonen-Ward & Luukkonen, 2005). The area can be divided into three granitoid complexes and two supracrustal suites (Figure 4.1). These are, from the north to the south: the Kemihaara-Vintilänkaira granitoid complex (KVGC), the Tulppio metavolcanic belt (TVB), the Ahmatunturi granitoid complex (AGC), the Tuntsa metasedimentary belt (TSB), and Naruska granitoid complex (NGC). The ultramafic rocks of the ELAD are found in several larger complexes and as ultramafic plugs of varying size, unevenly distributed in the granitoids and metasedimentary rocks of the ELAD.

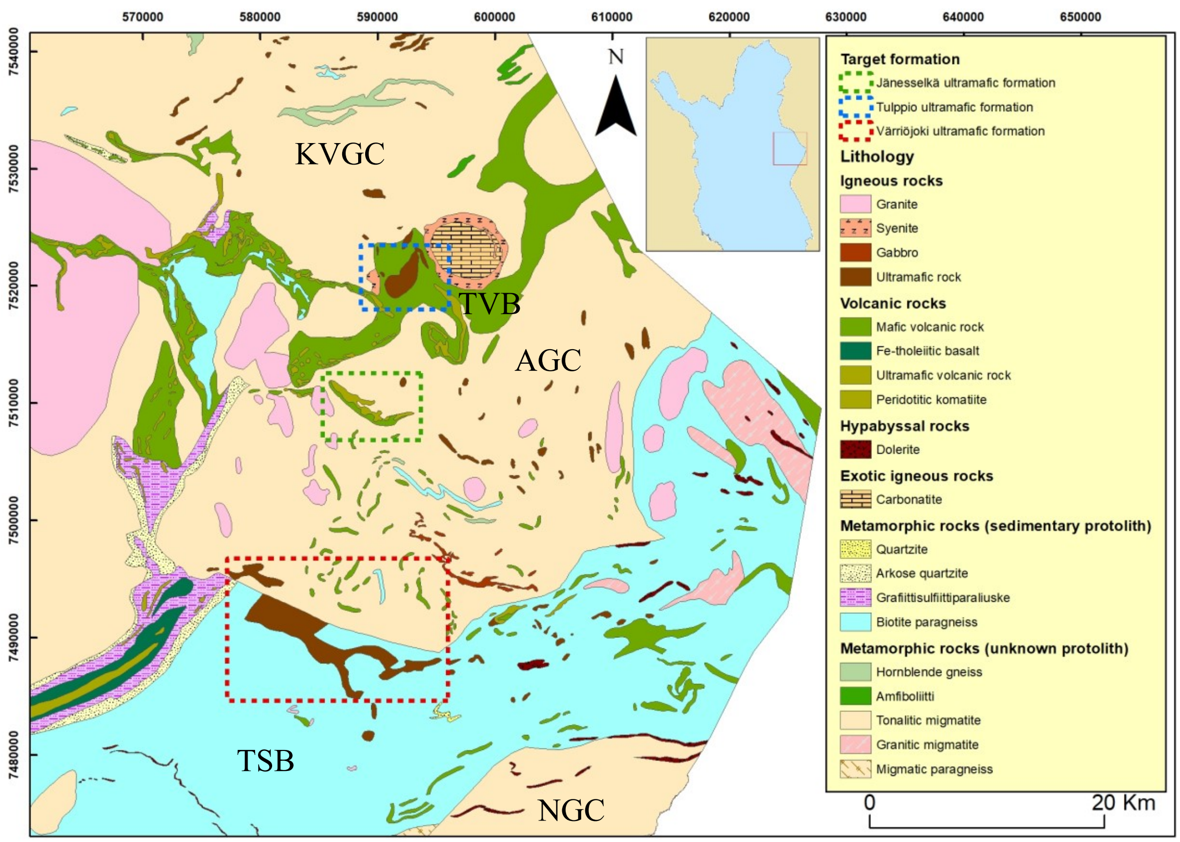

Figure 4.1: Lithological map of the Eastern Lapland Archean domain. Five lithotectonic provinces are marked by abbreviations (KVGC – Kemihaara-Vintilänkaria granitoid complex; TVB – Tulppio metavolcanic belt; AGC – Ahmatunturi granitoid complex; TSB – Tuntsa metasedimentary belt; NGC – Naruska granitoid complex). Three target ultramafic complexes of this study are highlighted with dashed rectangles. Modified after Bedrock of Finland – DigiKP.

4.1.1 Kemihaara-Vintilänkaira granitoid complex

The Kemihaara-Vintilänkaira granitoid complex (KVGC) is the northernmost part of the ELAD. The area can be divided to the southern (Vintilänkaira) and northern (Kemihaara) subdivisions based on more mylonitic nature of gneisses in the northern area (Juopperi, 1994). In Kemihaara, the dominating rock type is fine-grained tonalitic gneiss (Mikkola, 1941). Larger granitic units are also present, from which the Marjavaara granite, classified as syenite (Vartiainen & Woolley, 1974), has been dated at 2.8 Ga (Juopperi & Vaasjoki, 2001). Some ultramafic units are present in the Kemihaara area. Based on geophysical data, the Sorvortanjoki complex is the biggest uniform body in the area. Other ultramafic suites of the Kemihaara area are, often clustered and relatively small ultramafic bodies in the eastern part of the area. The ultramafic rocks are often associated with amphibolite.

The Vintilänkaira area consist of tonalitic gneisses and cross-cutting granites and pegmatites. Granites in the southern parts of the Vintilänkaira probably belong to the Central Lapland granite complex and cross-cut Paleoproterozoic schists. In the northern parts of the area, granites are more migmatized in general. Ultramafic cumulates are found mainly in the eastern parts of the area. These are thought to be part of the Tulppio metavolcanic belt (Juopperi, 1994). Overall, the Kemihaara-Vinitlänkaira granitoid complex forms the least studied area of the ELAD.

4.1.2 Tulppio metavolcanic belt

The Tulppio metavolcanic belt (TSB), also referred to as the Tulppio suite (Juopperi, 1994; Heikura et al., 2010), is located south of the Kemihaara granitoid complex. It is E-W oriented and 70 km long, and the eastern parts of the belt extend across the national border. The Tulppio belt consist of ultramafic and mafic metavolcanic rocks, the former being recognized as cumulates of komatiitic lavas, the latter as submarine Mg-rich and Fe-rich tholeiitic lavas. In places, these rocks are associated with quartz-feldspar schists, amphibole- and garnet-rich aluminous schists, quartzites, and cherty rocks (Juopperi, 1994). All rocks in the area have undergone a relatively high degree of deformation and metamorphism and thus primary mineral facies are not present, save for interior parts of the biggest cumulate bodies, which show some primary textures and minerals (Heikura et al., 2010). The ultramafic rocks of the area consist of two different rock types: strongly deformed, unmagnetized, green to pale green chlorite-tremolite schists, interpreted as komatiitic lavas or tuffs (Juopperi & Vaasjoki, 2001), and strongly magnetized, less deformed ultramafic rocks, considered to represent komatiitic feeder-cumulates of the Archean komatiitic lavas. Whether these rocks are Archean or Paleoproterozoic is still uncertain (Juopperi & Vaasjoki, 2001) as age determination of these rocks is challenging.

The Tulppio metasedimentary belt hosts a couple of large ultramafic cumulate bodies. These are distributed along the strike of the belt, with the largest ones being Tulppio ultramafic complex, also referred in the literature as the Tulppio dunite (Papunen et al., 1977, Halkoaho, 2003), the Kuttusvaara ultramafic complex, and the Jänesselkä mafic-ultramafic complex. In this study, the ultramafic complexes of Tulppio and Jänesselkä are studied in detail. The bedrock of the Tulppio area is relatively poorly exposed. Together with the high degree of deformation, it has thus been difficult to form a clear stratigraphy for the Tulppio metavolcanic belt. A schematic statigraphic model of Tulppio belt by Virransalo (1985) distinguishes the metavolcanic rocks of Tulppio as one group, with the Kuttusvaara ultramafic complex representing the lowest part and Jänesselkä the topmost part of the sequence.

4.1.3 Ahmatunturi granitoid complex

The Ahmatunturi granitoid complex (AGC) is situated in the central part of the ELAD, between the supracrustal belts of Tulppio in the north and Tuntsa in the south. It is bordered by Paleoproterozoic schists of the Central Lapland greenstone belt in the west and Belomorian rocks in the Russian side of the national border. The rocks of Ahmatunturi consist dominantly of moderately but unevenly magnetized tonalitic gneisses (Juopperi, 1994). Granites are also found from the Ahmatunturi complex, with the largest intrusions being present in the western parts of the area. These include the emplacements of Sotatunturi and Lipakka. The former has a U-Pb zircon age of 2.90 Ga (Juopperi & Vaasjoki, 2001), whereas the tonalite of Mujuvaara in the southern part of the complex has been dated at 2.83 Ga (Juopperi & Vaasjoki, 2001). Abundant amounts of mafic and intermediate fragments and relics are present within the granitoids proximal to the Tuntsa metasedimentary belt. In places, these rocks form migmatites with later-intruded granites.

4.1.4 Tuntsa metasedimentary belt

The Tuntsa metasedimentary belt (TSB), also referred to as the Tuntsa-Savukoski formation (Mikkola, 1941) or the Tuntsa suite (Juopperi, 1994), extends from Savukoski towards NE-E, across the national border. It is approximately 90 km long and bordered by the ~2.9 Ga Ahmatunturi granitoid complex in the north, Paleoproterozoic schists in the west, the ~2.7 Ga Naruska granitoid complex in the south, and Belomorian rocks in the east.

The Tuntsa metasedimentary belt consists predominantly of non-magnetized quartz-feldspar and mica gneisses and their equivalent migmatites. These rocks are interpreted to represent greywackes derived from late Archean crust (Kivisaari, 2008; Juopperi, 1994). Amphibolites and amphibolite-chlorite schists of the area correspond to the Tulppio metavolcanic rocks on the basis of their chemical composition (Juopperi & Vaasjoki, 2001). Ultramafic cumulates, the Värriöjoki complex as the biggest uniform body, are also present. Usually ultramafic rocks are found as plugs scattered throughout the TSB, with some of them associated with gabbroic dykes, especially in the proximity of the Ahmatunturi granitoid complex. The ultramafic units of the area are easily distinguished as distinct magnetic anomalies.

Many types of felsic intrusive rocks have also been observed in the area (Juopperi, 1994). Several meters thick tonalitic dykes are abundant at the contact in Sorsatunturi – Kuskoiva – Rakitsaiset area, in the northern parts of the TBS. According to Mikkola (1941), the granite in the Sauoiva area, in the northernmost parts on the Finnish side of TSB, differs significantly from the other granites of the ELAD. In this area, gneisses have undergone almost complete melting to produce granitic magmatism and thus have granitic nature (Juopperi, 1994). Gneisses of this type are abundant also at the margin of TSB and the Naruska granitoid complex. Pegmatites are common especially in the central and northern parts of the TSB. These are often stratiform and boudinaged, but still seem to cross-cut the surrounding gneisses (Juopperi, 1994).

Two different types of diabases have been described from the Tuntsa metasedimentary belt: thin, strongly magnetic, Fe-tholeiitic dykes in the western and southern parts of the area and gabbroic, weakly magnetized dykes in the Peuratunturi area. The latter can be hundreds of meters wide and they have preserved their primary magmatic mineral assemblages (Juopperi, 1994).

4.1.5 Naruska granitoid complex

The Naruska granitoid complex in the SE corner of the ELAD is limited by the Tuntsa metasedimentary belt in the north and Paleoproterozoic schists in the south and the west. Towards the east, NGC extends across the Russian border. The geology of NGC is similar to the other granitoid complexes in the area: the common rock types are, in places migmatized, tonalitic to granitic gneisses (Juopperi, 1994). Fragments and relics of quartz-feldspar schists and amphibolites are abundant within the gneisses. Diabase dykes cross-cut all these lithological units.

The contact between the NGC and the TSB is not unambiguous. Mylonitic nature of some rocks in the proximity of TSB suggests a tectonic contact (Juopperi, 1994). However, some observations show a gradational transition from coarse gneisses belonging to the NGC to paragneisses of the TSB. More recent interpretations suggest one geotectonic unit, in which the NGC represents a deeper erosional level (Juopperi & Vaasjoki, 2001).

Multiple age determinations from the area were carried out by Juopperi & Vaasjoki (2001). These include zircon U-Pb dating of a tonalite from Kepperivaarat (2.70 Ga) and a granite from Suoltijoki (2.72 Ga), as well as a titanite U-Pb dating of a cross-cutting metadiabase from Takatunturi (1.89 Ga). The latter shows similar chemical composition to the Fe-tholeiitic dykes in TSB (Juopperi, 1994).

4.2 Tectonic and metamorphic evolution of the ELAD

The ELAD is considered to represent the north-easternmost extent of the Karelian province, which, together with the Murmansk province, form the Archean crustal nuclei of the Fennoscandian shield (Bogdanova & Bibikova, 1993; Slabunov et al., 2006a; Luukas et al., 2017). Formation of the Karelian and Murmansk crustal rocks were related to late Archean and early Proterozoic accretionary-collisional processes (Slabunov et al., 2006b), from which the 2.9–2.6 Ga Lopean (Gaal & Gorbatschev, 1987) and 2.5–2.1 Ga Lapland – Kola (Daly et al., 2006) orogenies produced the majority of the crust in the northern parts of the shield. The majority of the age determinations from the crustal rocks of the ELAD (Juopperi & Vaasjoki, 2001) and Belomorian belt (Bogdanova and Bibikova, 1993) correspond to the time span of the Lopean orogeny (2.9–2.6 Ga) (Gaal & Gorbatschev, 1987).

The Belomorian belt can be seen as analogous to the ELAD, showing similar rock types and ages (Juopperi & Vaasjoki, 2001; Slabunov et al., 2006b). There is no consensus as how these two provinces are related to each other; however, as a tectonic province, the ELAD has usually been included in the Belomorian belt (Gaal & Gorbatschev, 1987; Bogdanova and Bibikova, 1993; Balagansky et al., 2001; Slabunov et al., 2006a). Some studies have interpreted only the Tuntsa metasedimentary belt as part of the Belmorian belt (Hölttä & Heilimo, 2017), whereas Luukas et al., (2017) suggest that the ELAD and the Belomorian belt can both be included in the Karelian tectonic province, as no sufficient evidence of the Belomorian belt being separated from the Karelian craton have been presented.

Medium- to high-grade metamorphism and multi-phase deformation have thoroughly influenced the ELAD (Juopperi, 1994). Primary structures and the mineral associations in the supracrustal rocks are not preserved, except for the inner parts of the biggest ultramafic cumulates (Vuollo, 1986; Halkoaho, 2003; Törmänen et al., 2007; Heikura et al., 2010). Gently SW-dipping thrust structures are dominant features in all parts of the domain.

The deformational history of the granitoid complexes in the ELAD is vaguely known. However, models for tectonic reworking of tonalitic gneisses in Belomorian belt have been put forward (Balagansky et al., 2001; Daly et al., 2006). These can provide an insights into the evolution of the granitoid complexes of the ELAD, as these rocks can be considered to represent the same lithotectonic unit (Slabunov et al., 2006a; Hölttä & Heilimo, 2017).

Four different deformation phases have been recognized in the Tulppio metavolcanic belt (Virransalo, 1985), the oldest representing the main metamorphic event. Typical metamorphic minerals in the komatiites are anthophyllite, tremolite, talc, chlorite and forsteritic olivine. In addition, enstatitic pyroxene and plagioclase are found in some basaltic komatiites of the Tulppio belt. Metapelites in TVB contain staurolite, cordierite, garnet, sillimanite, kyanite and andalusite (Virransalo, 1985).

Metamorphism of the Tuntsa metasedimentary belt has been the target of some studies (Kivisaari, 2008; Hölttä & Heilimo, 2017). A typical mineral assemblage in the metasedimentary rocks is staurolite-biotite-quartz-plagioclase ± garnet ± kyanite ± chlorite ± cordierite ± muscovite (Hölttä et al., 2014). U-Pb age determinations from the metasediments show two age groups, with maximum deposition ages of 2.84–2.80 Ga and 2.69–2.67 Ga (Hölttä et al., 2014).

There are two similar stratigraphic models for the supracrustal rocks of the ELAD (Virransalo, 1985; Halkoaho, 2003). Virransalo (1985) divided the stratigraphy of the area to the Tulppio group, the Ruuvaoja group and the Kiimaselkä ultramafic complex. These sequences are separated by discordances (Virransalo, 1985; Halkoaho, 2003). Both stratgraphical models suggest tholeiitic basalts of Tulppio metavolcanic belt to represent the lowest supracrustal unit on the crustal basement. These are overlain by the majority of the komatiitic units of TVB, in turn overlain by the second metatholeiitic basaltic unit. These are followed by the felsic metavolcanites and metasediments, metatholeiites, paragneisses and quartzites of the Rouvakonselkä formation. The topmost ultramafic unit in the Tulppio group is the komatiitic rock suite of Jänesselkä.

Ruuvaoja group includes, from bottom to top, skarn conglomerates, quartzites, mica schists, carbonate rocks, and a metatholeiitic unit, in which the Värriöjoki complex is included. The Kiimaselkä formation is considered as the topmost supracrustal unit in the stratigraphy and it consists of pyroclastic metakomatiites (Virransalo, 1985).

Both tectonic models underline the uncertainty in interpretations due to poor exposure of the contacts of the different lithological units. In addition, extensive deformation hinders the stratigraphy of the area (Virransalo, 1985; Juopperi, 1994; Halkoaho, 2003).

4.3 Ultramafic complexes of interest

In this thesis, three ultramafic complexes of ELAD (Figure 4.1) are described in detail. These ultramafic bodies were selected on the basis of their location, geophysical properties, and previous results. The ultramafic complexes of Tulppio and Jänesselkä, 10 km apart from each other, have been interpreted to belong to the Tulppio metavolcanic belt. The Värriöjoki ultramafic complex is located in the Tuntsa metasedimentary belt, at the contact of the Ahmatunturi granitoid complex, approximately 20 km south of the TVB.

4.3.1 Tulppio ultramafic complex

The Tulppio ultramafic complex (Figure 4.2), also referred to as the Tulppio dunite (Papunen et. al., 1977; Heikura et al., 2010), is the biggest ultramafic body in the Tulppio metasedimentary belt. It is located in the central parts of the TVB, close to the Phanerozoic Sokli carbonatite. Tulppio ultramafic complex is 5 km by 2 km in size and, according to geophysics, it extends to the depth of 2 km (Heikura et al., 2010). The main ultramafic body is not well exposed, yet some outcrops are found in the area. The main rock type is dunite with some metamorphic olivine. In the central parts of the dunitic body, olivine is magmatic, however. Towards the margin of the body, serpentinization of olivine intensifies and quartz veining becomes prominent (Heikura et al., 2010). Other common metamorphic mineral assemblages in the dunite are serpentine-talc, serpentine-tremolite and serpentine-enstatite. Gabbroic rocks are also found within the ultramafic complex. These may be interpreted as differentiates of the Tulppio dunite (Halkoaho, 2003). The rocks surrounding the Tulppio ultramafic complex are amphibolites, interpreted as tholeiitic lavas, volcanic and sedimentary schists, and granitoids. Skarns are common along the eastern margin of the dunitic body (Heikura et al., 2010).

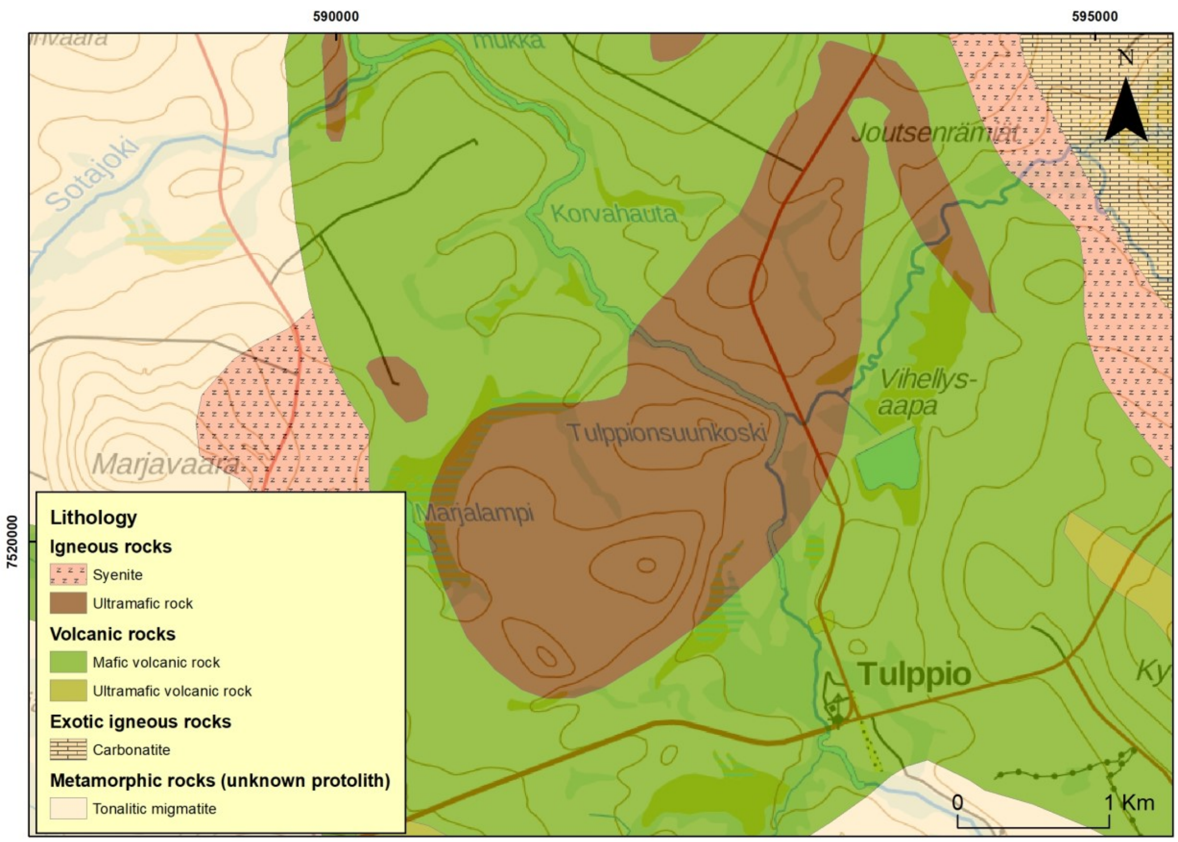

Figure 4.2: Lithological map of the Tulppio ultramafic complex. As presented in DigiKp - Bedrock Map of Finland.

The ore potential of the Tulppio ultramafic complex can be considered notable. During exploration project by the GTK, a Ni-(PGE) mineralization was located in the central parts of the dunite, with the best drill core intersections being in drill core R0320; 3m @ 1.12ppm Pt+Pd, with 0.49 % Ni (Heikura et al., 2010).

The Tulppio ultramafic complex has been suggested to represent a feeder-cumulate for komatiitic magmas of the TVB (Juopperi, 1994; Halkoaho, 2003; Juopperi & Vaasjoki, 2001) or a thick komatiitic sequence of a komatiitic lava flow (Halkoaho, 2003).

4.3.2 Jänesselkä mafic-ultramafic complex

The Jänesselkä mafic-ultramafic complex (Figure 4.3) is located south of TVB, within the AGC. It is NW-SE oriented, 5 km by 1 km in size. The terrain is relatively easy to access and outcrops are common. The ultramafic rocks include metamorphosed ultramafic cumulates and lavas and associated pyroxenites and gabbroic rocks (Liimatainen, 2003). In the SE part of the complex, ultramafic rocks are heavily deformed tremolite-chlorite schists and tremolite-serpentine rocks. Towards the center of the S part of the complex, the rocks become less deformed and show relict cumulus textures. In cumulus terminology, these rocks are ortho- to mesocumulates with olivine or pyroxene (here completely pseudomorphed) as cumulus minerals. Gabbros and pyroxenites are found in contact with the ultramafic rocks in the eastern margin of the central parts of the ultramafic complex. Mafic volcanic rocks are also found at the southern margin of the complex. Rocks in the NW part of the complex include serpentinites, tremolite-serpentine rocks, basic to intermediate volcanic rocks and arkose quartzites (Liimatainen, 2003). Quartzites are found also in the southern parts of the area. These and the ultramafic rocks of Jänesselkä are surrounded by migmatized mica schists (Virransalo, 1985).

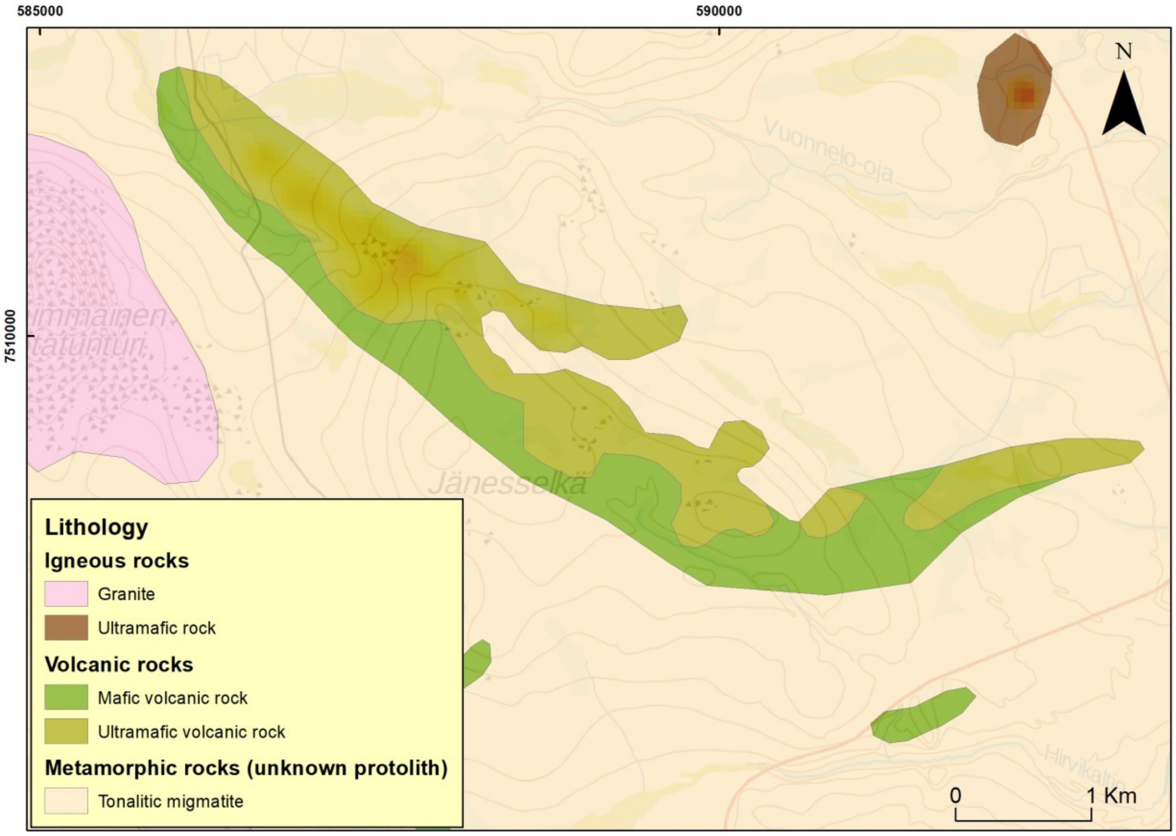

Figure 4.3: Lithological map of the Jänesselkä mafic-ultramafic complex, as presented in DigiKp - Bedrock Map of Finland.

4.3.3 Värriöjoki ultramafic complex

The Värriöjoki area (Figure 4.4) hosts several ultramafic bodies, from west to east: Siurujoki, Värriöjoki, Liessijoki, Leppäselkä and Venehaara. All the major ultramafic bodies of the area form a NW-W SE-E oriented belt, approximately 20 km long. In this study, the Värriöjoki ultramafic complex comprises the main block of Värriöjoki and smaller blocks included are Liessijoki, Leppäselkä and Venehaara, as there is no evidence of Siurujoki block belonging to the Värriöjoki ultramafic complex.

The Värriöjoki ultramafic complex, also known as the Värriöjoki intrusion (Vuollo, 1986; Lahti et al., 2007), is the largest ultramafic complex of ELAD. It is located at the border of TSB and AGC, delimited in the north by this contact. In the north, at a distance of 2 km from the main ultramafic block (Värriöjoki block), is the ultramafic formation of Siurujoki. To the SE-E are the blocks of Liessijoki, Leppäselkä and Venehaara. On the current erosional surface these bodies seem isolated. However, according to geophysics, these ultramafic bodies may be connected to each other and also to the main block (Lahti et al., 2007).

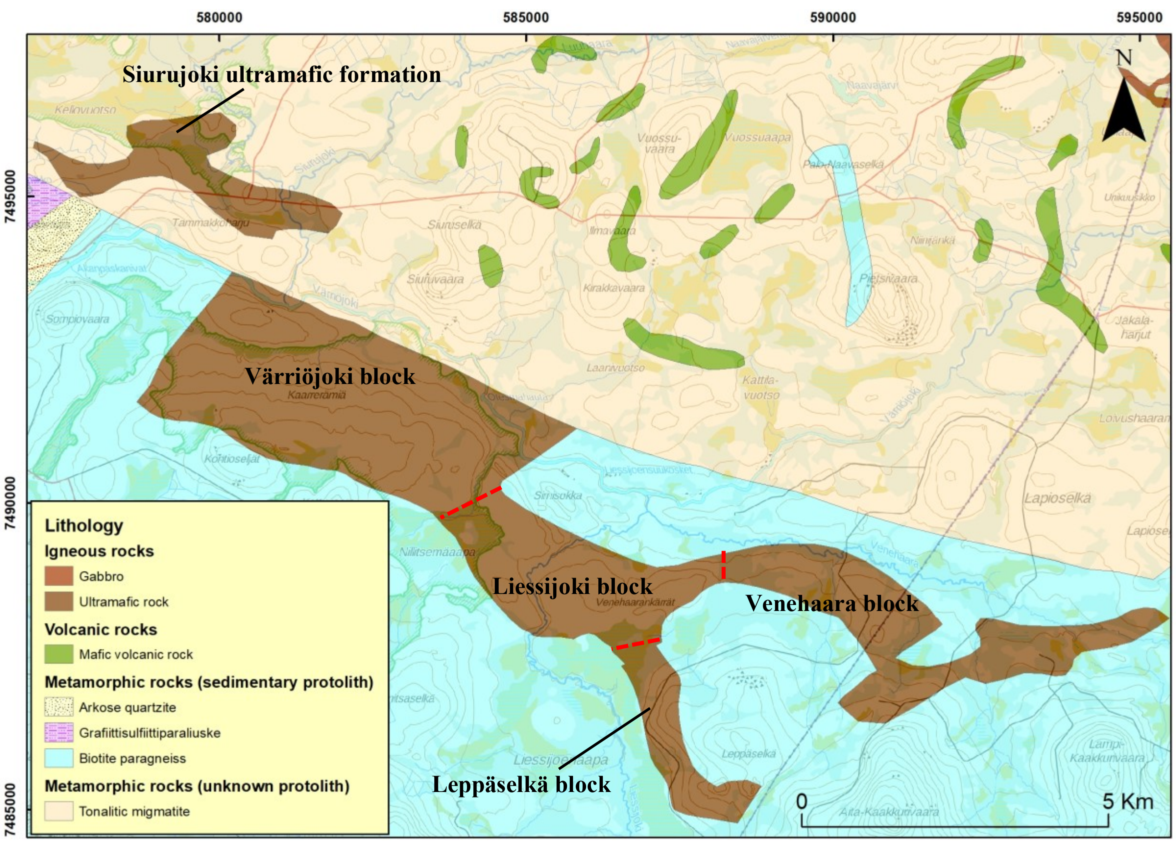

Figure 4.4: Lithological map of the Värriöjoki ultramafic complex, as presented in DigiKp - Bedrock Map of Finland. Red dashed lines represent division of Värriöjoki ultramafic complex in to four ultramafic blocks (Värriöjoki, Liessijoki, Leppäselkä, and Venehaara).

The Värriöjoki block consists of monotonous, undeformed dunite (Vuollo, 1986; Törmänen et al., 2007). These dunites are serpentinized, but still show cumulate texture. The ultramafic body often has a 10-cm-thick weathered surface. Some peridotites and pyroxenites are also present, especially at NE and SW margins of the dunitic body in the main block (Törmänen et al., 2007). Most of the peridotites are interpreted as wehrlites (Peltoniemi, 1984; Vuollo, 1986). In the southern parts of the body, a serpentinized and amphibolitized, 50-m-wide and

700-m-long peridotite unit is found. This body has a thin (20 cm) differentiated olivine cumulate part with more clinopyroxene (Vuollo, 1986). Peridotites and pyroxenites of the area are easily distinguished on the basis of their knotty surface that relates to poikiloblastic clinopyroxene.

In the terms of rock type, the other bodies of the ultramafic complex of Värriöjoki are similar to those of the main block, with an exception of the Leppäselkä block consisting mostly of olivine mesocumulates. In the Venehaara and Liessijoki blocks, olivine adcumulates dominate, with pyroxenites and amphibolites prevailing closer to margins of the bodies. However, as outcrops become less abundant towards the east, geological understanding about the complex in these areas is mainly based on drillings and geophysical studies (Lahti et al., 2007; Törmänen et al., 2007). The margins of the ultramafic complex are altered. Common minerals in such parts are serpentine, amphibolite, talc, and carbonates (Vuollo, 1986).

The first studies of the Värriöjoki ultramafic complex (Peltoniemi, 1984; Piirainen, 1985) interpreted it as a gabbro-werhlite feeder cumulate. According to these studies, the Värriöjoki ultramafic complex shows similarities with the ultramafic rocks of east Finland (Törmänen et al., 2009). Later, petrological studies of Vuollo (1986) and Törmänen et al., (2007) have shown that the Värriöjoki ultramafic complex is most likely the feeder cumulate of komatiitic lavas. Whether these rocks are Archean or Proterozoic, is yet to be determined.

5 PRE-EXISTING MATERIAL AND DATA

The archived data from the ultramafic rocks of Tulppio, Jänesselkä and Värriöjoki, used in this study, originated from the studies and exploration projects carried out by the GTK and the universities of Turku and Oulu. The earliest analytical data are from the Lapland nickel project of the Turku University (Papunen et al., 1977). Other sources of data are: Oulu University ore project on Archean areas (Piirainen, 1985), a Master's thesis on the Värriöjoki ultramafic complex (Vuollo, 1986), Lapland volcanic project (Lehtonen et al., 1998) by the GTK, and the komatiite project by University of Turku (Papunen, 2003). The ultramafic complexes of Tulppio and Värriöjoki have also been explored by Rautaruukki Oy and the GTK (Vuotovesi, 1984; Iljina, 2003; Iljina 2009; Törmänen et al., 2007; Heikura et al., 2010) and drill core data from these exploration projects are available.

5.1 Thin sections

Polished thin sections from the GTK exploration projects from Tulppio (Heikura et al., 2010) and Värriöjoki (Törmänen et al., 2007) were available for this study, including 31 polished thin sections from drill cores from Tulppio and 74 from Värriöjoki. From these, six thin sections were selected for closer examination and determination of mineral chemistry. The selection criteria are described in Chapter 6.

5.2 Geochemical data

A dataset of 1890 samples, from the projects mentioned above, was provided by the GTK for this study. The dataset comprises of 151 drill core samples and 283 field samples. From these data, geochemical data from ultramafic rocks from the target complexes were selected by qualitative criteria presented in the following sections.

5.2.1 Major element data

The dataset by the GTK contains 434 analyses from the target complexes. From these, 382 samples of komatiitic composition (MgO > 18 wt.%; SiO_2 > 52 wt.%) were selected for closer examination. In addition, two samples with a composition of komatiitic basalt from Värriöjoki ultramafic complex and seven mafic samples from Jänesselkä mafic-ultramafic complex were included. For some of these old analyses (Piirainen, 1985; Lehtonen et al., 1998), the analytical method is unclear. However, X-ray fluorescence spectroscopy (XRF) is mentioned in most cases. The other method for major element data is atomic absorption spectrometry (AAS). This is restricted to the data from the years 1970–1980 (Piirainen, 1985; Lehtonen et al., 1998). The possibility of having data acquired by two different analyzing methods was notified in the data selection and comparability of the old data to the modern data was evaluated. Level of uncertainty is slightly increased as pre-2000 data are included, but considering major elements, this is not seen as a major source of distortion, and hence these analyses are included in the major element examinations.

5.2.2 Platinum-group elements

Platinum-group element data from rocks with komatiitic composition was available for 254 samples. From these, 175 were included in this study, as these were analyzed in the same laboratory (method code 705P) by Labtium Oy (Törmänen et al., 2007; Heikura et al., 2010). All selected analyses were performed after the year 2000. Post-2000 PGE analyses were not available from the Jänesselkä mafic-ultramafic complex, whereas 46 analyses from the Tulppio ultramafic complex and 129 from Värriöjoki ultramafic complex were considered comparable with the new data of this study.

5.2.3 Rare earth elements

The primary selection criterion for REE data was the analytical method used. Post-2000 analyses were available for 254 komatiitic samples from target complexes. As it was uncertain whether zero values in the dataset represent elements under detection limit or elements not analyzed, the final selection of data was done by including samples only from most recent studies (Iljina, 2003; Törmänen et al., 2007; Heikura et al., 2010) with good documentation of methods. This reduced the amount to 159 analyzes: 30 from Jänesselkä, 21 from Tulppio, and 64 from Värriöjoki. All selected analyses are ICP-MS analyses and done by Labtium Oy.

5.3 Mineral chemistry

Mineral analyses from the Master's thesis by Vuollo (1986) were available for this study, including total of 50 olivine analyses from the Värriöjoki ultramafic complex. The analyzed samples were from the main block of the complex. These were examined and compared to the new analytical data, as presented in the discussion.

6 RESEARCH METHODS

Methods of research are presented in the order they were performed during the two years of the project, with the field studies having started in the summer 2017. Petrographical studies were performed after the 2017 field season, and the majority of the geochemical data were achieved and studied between and after the field seasons of 2017 and 2018.

6.1 Field studies

Field studies were carried out during the summers of 2017 and 2018 as a part of a regional ore potential project of ELAD by the GTK and University of Helsinki (Haapala et al., 2018). The targets of these studies were ultramafic rocks with special interest in komatiitic suites that have not been analyzed using modern geochemical methods. Mapping and sampling was planned based on previous studies, bedrock maps and, most importantly, geophysical data. Due to long distances and poor road network, transportation was done by cross-country vehicles and ATVs. At longest, single targets required also additional couple of tens of kilometers travelling by foot. During the four months of field studies, a total of 128 new observations (Figure 6.1) from mafic to ultramafic rocks were made, 21 from locations with komatiitic rock previously unrecorded. In total, 127 samples were collected from the least weathered and deformed parts of boulders and outcrops and prepared for analysis. As the terrain of the study area was glaciated during the Pleistocene, the sampling required an estimation about the locality of every sampled boulder.

Field studies considering the ultramafic complexes of this study were focused on the Jänesselkä mafic-ultramafic complex, as the ultramafic complexes of Tulppio and Värriöjoki have been studied previously. These targets were visited, and in order to obtain a better overall picture, sampling was performed in the eastern parts of the ultramafic complex of Värriöjoki. In total, 29 samples were collected – of these seven were from outcrops previously not found.

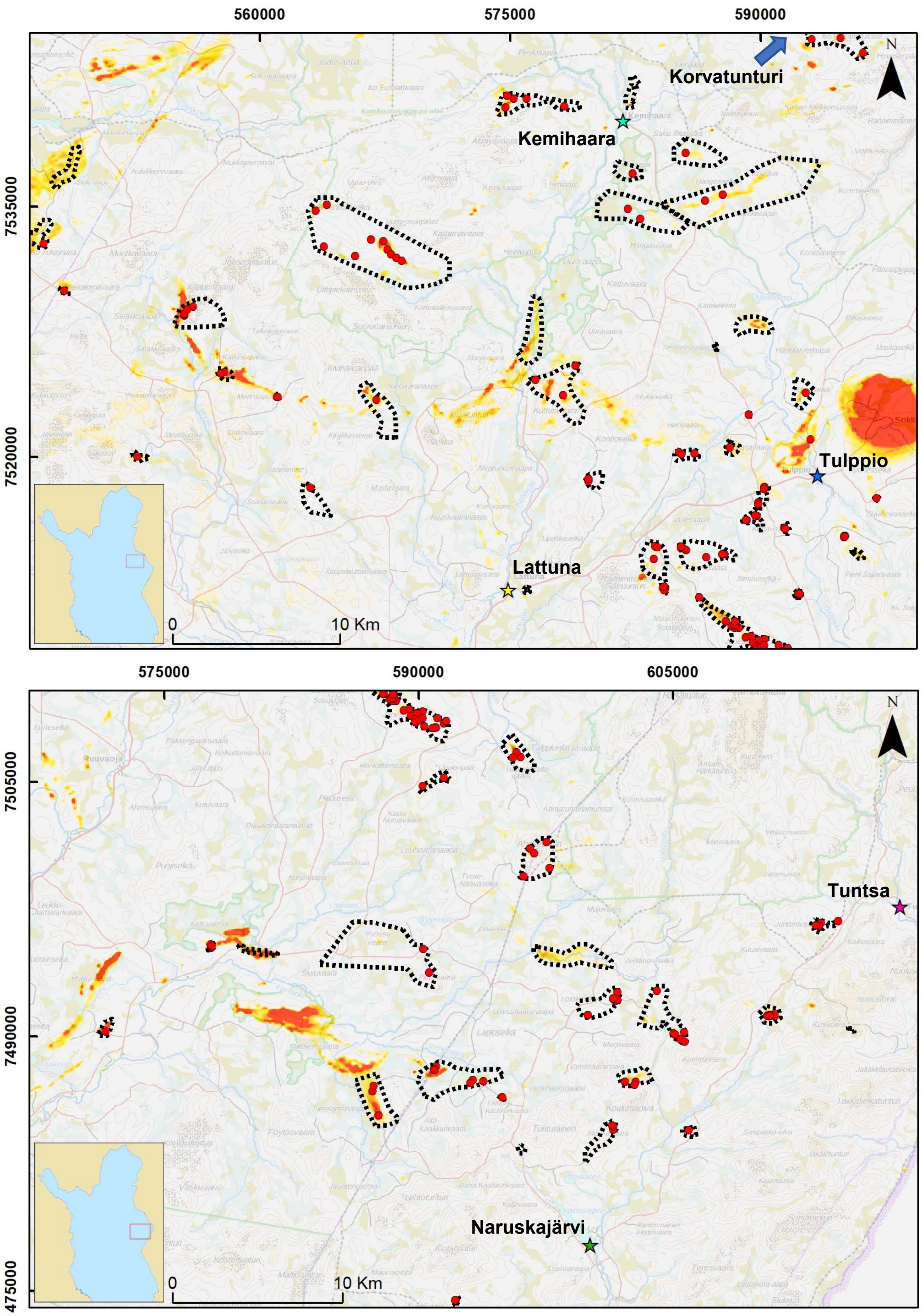

Figure 6.1: Two composite magnetic anomaly – topographic maps illustrating the distribution of mapped areas of the ELAD during the summers 2017 and 2018. Red dots represent samples collected during field studies.

6.2 Petrography

Thin section samples for petrographic examination were selected from the main lithological units of the target complexes. In total 10 samples were studied, three from Tulppio, three from Jänesselkä and four from Värriöjoki (Table 6.1). Quantitative mineral chemical analyses were carried out from six of the thin sections. Petrographic studies were mostly performed with an optical microscope, but polarized reflected light microscopy was used for identification of spinel group minerals and sulfides.

6.3 Geochemistry

Sample preparation was performed by the author and the project research team at the University of Helsinki. This included sawing of the samples into fragments of desired size for Labtium Oy and the thin section laboratory. Sample preparation was finished at Labtium Oy, involving crushing and pulverization. Method codes provided below are based on those of Labtium Oy and procedures (including detection limits) are described at: http://www.labtium.fi/en/our-services/exploration-and-mining.

Major element analyses were performed on 22 samples: 17 from the Jänesselkä mafic-ultramafic complex and five from the Värriöjoki ultramafic complex. The method used was pressed powder pellet XRF-analysis (175X). Precious metal analyses were performed for all 22 samples. The method used was Fire Assay -ICPOES analysis (705P). Rare earth element analyzes were done for seven samples from Jänesselkä mafic-ultramafic complex and one sample from Värriöjoki ultramafic complex. These included seven ultramafic rocks and one gabbro (JHTE-2017-35.2). Analyze method used was inductively coupled plasma mass spectrometry (ICP-MS) (308M).

Table 6.1: Samples from the target areas from the 2017–2018 field studies with analysis methods for each sample listed. The six samples at bottom are from drill cores from previous studies on Tulppio (Heikura et al., 2010) and Värriöjoki (Törmänen et al., 2007) ultramafic complexes. Analytical data from these samples is included in the dataset described in Section 5.2.

Sample ID	Target	Rock Type	XRF (175X)	PGE (705P)	REE (308M)	Thin section
JHTE-2017-35.2	Jänesselkä	gabbro	x	x	x	x
HMHO-2017-20.1	Jänesselkä	serpentinite	x	x		
HMHO-2017-22.1	Jänesselkä	tremolite-serpentine rock	x	x		
HMHO-2017-24.1	Jänesselkä	gabbro	x	x		
HMHO-2018-9.1	Jänesselkä	talc-serpentine rock	x	x		
PSHA-2017-18.1	Jänesselkä	amphibolite	x	x		
PSHA-2017-19.1	Jänesselkä	tremolite-serpentine rock	x	x	x	
PSHA-2017-20.1	Jänesselkä	tremolite-serpentine rock	x	x		
PSHA-2017-24.2	Jänesselkä	serpentinite	x	x		
PSHA-2017-25.1	Jänesselkä	serpentinite	x	x	x	x
PSHA-2017-26.1	Jänesselkä	serpentinite	x	x		x
PSHA-2017-27.1	Jänesselkä	talc-chlorite schist	x	x	x	
PSHA-2017-3.1	Jänesselkä	serpentine-tremolite rock	x	x	x	
PSHA-2018-5.1	Jänesselkä	tremolite rock	x	x	x	
PSHA-2018-6.1	Jänesselkä	gabbro	x	x		
PSHA-2018-7.1	Jänesselkä	chlorite-tremolite schist	x	x	x	
PSHA-2018-8.1	Jänesselkä	chlorite-tremolite schist	x	x		
HMHO-2017-38.1	Värriöjoki	serpentinite	x	x		
HMHO-2017-38.2	Värriöjoki	tremolite-serpentine rock	x	x	x	
JHTE-2017-24.1	Värriöjoki	ultramafic rock	x	x		
JHTE-2017-25.1	Värriöjoki	olivine adcumulate	x	x		
JHTE-2017-25.2	Värriöjoki	olivine adcumulate	x	x		x
R21@222.15	Värriöjoki	olivine-serpentine rock				x
R10@121.55	Värriöjoki	serpentinite				x
R10@196.35	Värriöjoki	metaperidotite				x
R0318@15.70	Tulppio	dunite				x
R319@158.15	Tulppio	talc-chlorite-olivine rock				x
R0318@26.75	Tulppio	olivine-serpentine rock				x

6.4 Mineral chemistry

Samples for mineral chemistry analyses were selected on the basis of the level of alteration and representativeness on the target complexes, with samples showing the least post magmatic modification being favored in the selection. Mineral chemical analyses were performed at GTK electron probe microanalysis laboratory in Espoo. These included 19 olivine and 42 chromite analyzes from two thin sections from Tulppio, and 23 olivine and 57 chromite analyses from two thin sections from Värriöjoki. Any analyses from the Jänesselkä mafic-ultramafic complex were not included as magmatic minerals were not found. Analyses were performed in a manner of each single olivine grain being analyzed with five sample points, from the core to the rim. Electron probe microanalyzer used was Cameca SX 100. Olivine analyses were run with acceleration voltage of 20 kV as beam current and diameter were set to 60 nA and 1 µm. Chromite analyzes were run with acceleration voltage of 15 kV, beam current of 40 nA and beam diameter of 5 µm. Each chromite grain was analyzed from five points from the core to the rim. The author took part in the analyses under the supervision of Lassi Pakkanen, GTK.

7 RESULTS

The results of the field studies are given first. These are followed with presentation of petrography for main lithological units forming each target complex. Geochemistry, including the major elements and trace elements, and mineral chemical analytical data, are given last, separately for each target.

7.1 Descriptions of the target complexes

As already pointed out in the method section, the Jänesselkä mafic-ultramafic complex is the least known target of the three targets selected and, consequently, it received the main emphasis of the field studies. Ultramafic complexes of Tulppio and Värriöjoki are discussed with less new data, mostly based on the diamond drill cores from previous studies (Törmänen et al., 2007; Heikura et al., 2010).

7.1.1 Jänesselkä mafic-ultramafic complex

Area of Jänesselkä (Figure 7.1) can be reached from the south and the west sides of the complex, the nearest road being 2 km away. As previous studies on the ultramafic complex of Jänesselkä have focused exclusively on the northern parts of the area (Papunen et al., 1977; Iljina, 2003; Liimatainen, 2003), mapping and sampling was focused on the southern parts of the area. The area is easy to travel by foot with the exception of small peatlands on the edge of the NE side of the area.

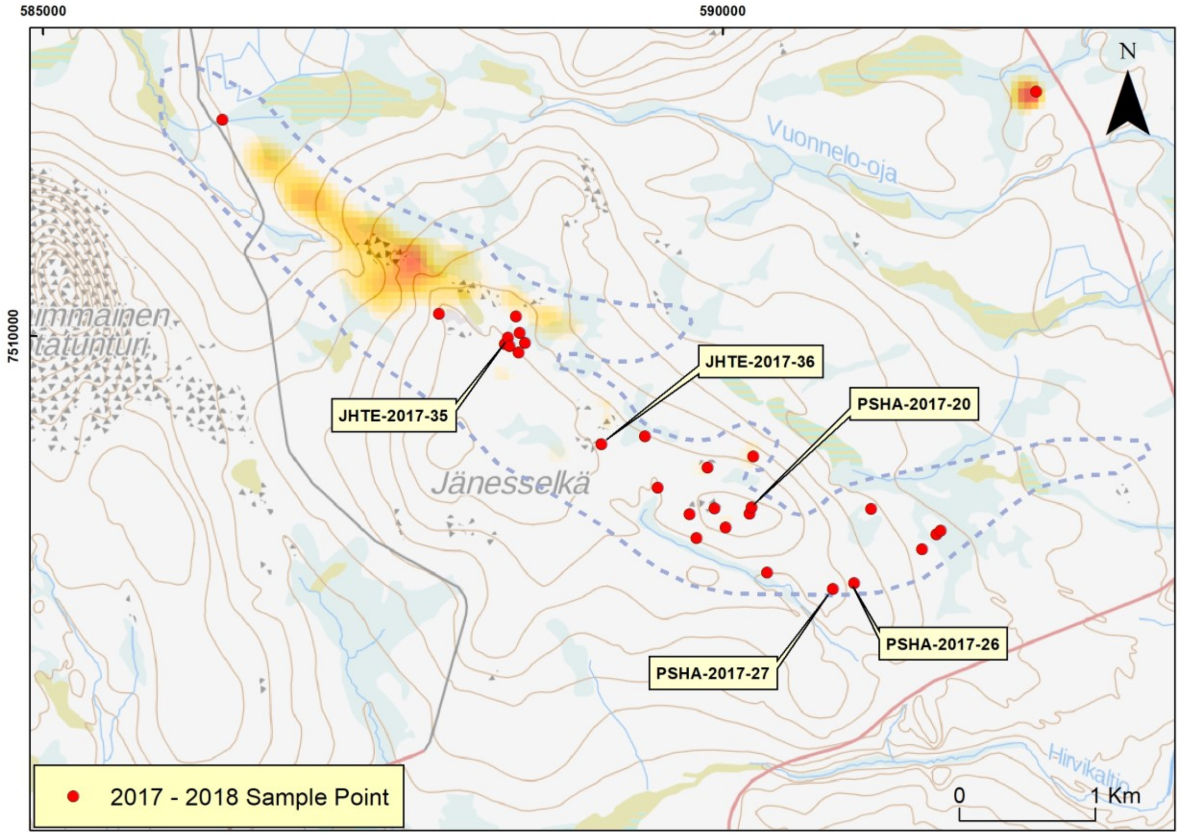

Figure 7.1: Composite map of the Jänesselkä area with the topography and magnetic anomalies illustrated. Dashed line represents the shape of the ultramafic complex as presented in DigiKp - Bedrock map of Finland. Samples identified in the figure are highlighted in the results. Map coverage as marked in Figure 4.1.

Outcrops are most abundant in topographically high areas and they often consist of large local boulders. These boulder fields are several hundred meters wide and often include some bedrock exposures (Figure 7.2). Towards the SE outcrops diminish and large local boulders dominate. At the southernmost end of the ultramafic complex, there are several small outcrops of talc-carbonate schists, which are the most heavily deformed rocks of the area.

Figure 7.2: Typical outcrop in Jänesselkä mafic-ultramafic complex. Outcrop (front) is surrounded by large local boulder field. Bedrock observation JHTE-2017-36 (x 7509209, y 589132) in the front.

The dominant rock types are serpentine-tremolite rocks (Figure 7.3) and chlorite-tremolite schists (Figure 7.4), the former likely representing ultramafic cumulates and latter their heavily deformed equivalents. Almost all rocks are at least moderately deformed with dominant gently SW-dipping thrust structures. Ultramafic cumulates are most abundant in the northern parts of the complex, where also the strongest magnetic anomaly is located. Ultramafic cumulates were also recognized in the central parts of the complex. This area is characterized by large boulder fields with outcrops in and around them. Relict poikilitic texture was found in some of these rocks.


Figure 7.3: Serpentine-tremolite rock (JHTE-2017-36.1), showing relictic poikilitic texture (nubs on the weathering surface). Jänesselkä mafic-ultramafic complex.

The most altered rocks with komatiitic composition are heavily deformed and often banded talc-chlorite schists. Large outcrops of this rock type were not found, but large local boulders were recognized in the SE parts of the complex. As the position of these rock bodies in relation to bedrock was not clear, reasonable interpretations of structural geology could not be constructed, although dominance of low SW-dipping features was distinct. Areas hosting non-cumulus komatiites do not contain strong magnetic anomalies associated with them, but still many of these rock bodies could be distinguished from surrounding non-magnetized gneisses on detailed magnetic anomaly maps. In addition to gneisses, non-cumulus komatiites are in contact with quartzites at the SW margin of the complex.

Figure 7.4: Outcrop of tremolite-chlorite schist (PSHA-2017-27; x 7508151,y 590812) in the southern parts of the Jänesselkä mafic-ultramafic complex. Complex folding and related crenulation appear especially at the northern side of the outcrop. Picture is to the south.

Gabbroic rocks with widespread compositions are found approximately 500 meters NW from the ultramafic cumulates in the center part of the complex. A gradual change from melagabbro to leucogabbro can be observed. In addition, an anorthosite fragment was found in the leucogabbro. The gabbroic rocks are surrounded by altered pyroxenites, with all rocks moderately deformed. Based on the observed gradual transition of rock types from mafic to ultramafic, gabbroic rocks and surrounding pyroxenites were interpreted to belong to the same system with ultramafic rocks by the research group.

7.1.2 Tulppio ultramafic complex

Tulppio ultramafic complex (Figure 7.5) is the least exposed of the three target complexes and lithological understanding of it is mainly based on drillings. Excluding the areas around the Tulppio River, the terrain is easy to travel by foot. Access to the main dunitic body is from the west side of the complex by a forest service road. The strongest magnetic anomaly is present in the northern parts of Tulppionkariste. In this area, drilling sites and research trenches can be found.

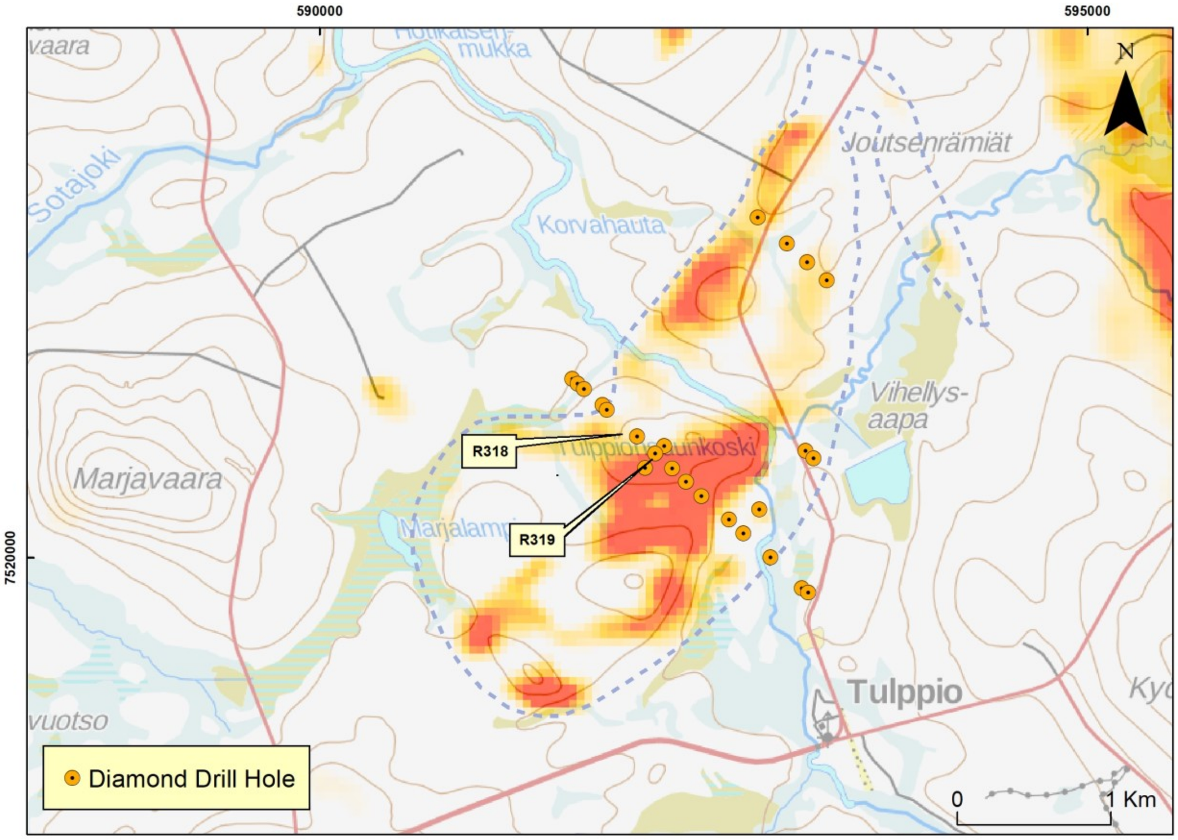

Figure 7.5: Composite map of the Tulppio ultramafic complex with topography and magnetic anomalies illustrated. Shape of the complex is marked with the dashed line as presented in DigiKP – Bedrock of Finland. Diamond drill holes (DDH) from exploration project carried out by the Geological Survey of Finland (Heikura et al., 2010) are marked with the two DDHs labeled. Thin sections from Tulppio for this study are originated from these two DDHs. Strong magnetic anomaly in the eastern side of the Tulppio ultramafic complex is the Sokli carbonatite. Map coverage as marked in Figure 4.1.

7.1.3 Värriöjoki ultramafic complex

The two easternmost ultramafic blocks (Leppäselkä, Venehaara) of Värriöjoki (Figure 7.6) are situated in a varying terrain. Excluding the well exposed southern tip of the Leppäselkä block, these are poorly exposed, as glacial deposits and peatlands dominate the landscape. Magnetic anomaly marking the Leppäselkä block is S-N oriented and runs along the western side of a low ridge. The rocks exposed are rather weakly deformed olivine cumulates. Bedrock outcrops disappear under thick sandy soil within a relatively short distance from the south to the north. Some boulder fields are present near the northern margin of the anomaly and consist of non-magnetized gneisses.

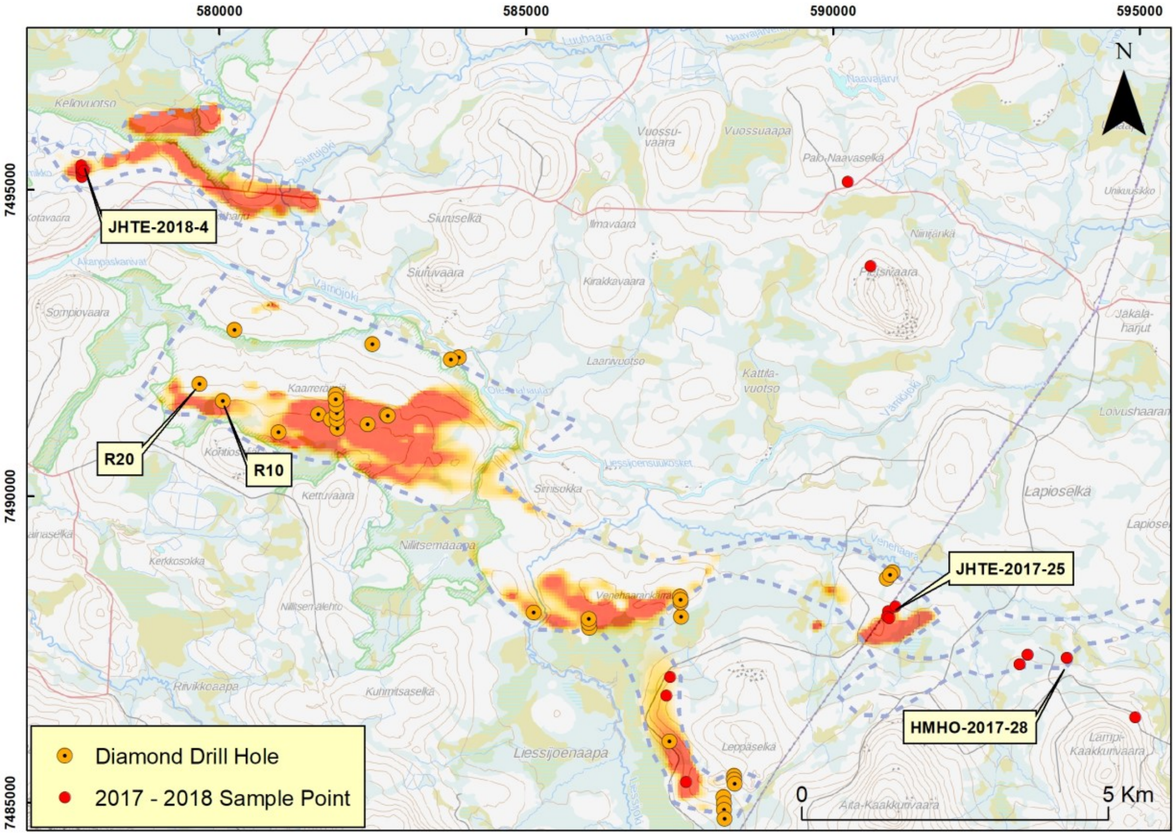

Figure 7.6: Composite map of Värriöjoki ultramafic complex with topography and magnetic anomalies illustrated. Dashed line represents the shape of the complex as presented in DigiKp - Bedrock Map of Finland. Sample points from the 2017 – 2018 field studies and diamond drill holes from the exploration projects (Vuotovesi, 1984; Törmänen et al., 2007) are marked on the map. Map coverage as marked in Figure 4.1.

Figure 7.7: Needle-like tremolite grains in a rock that probably represented an olivine adcumulate before metamorphism (JHTE-2017-25.1; x 7488003, y 590918). Western part of the Venehaara block.

The Venehaara block is covered by peat and sandy soils. Several ultramafic boulders are found in the northern margin of the magnetic anomaly. These included slightly deformed tremolite-olivine rocks (Figure 7.7) and undeformed olivine adcumulates, both with magmatic cumulate texture. In addition, weak magnetic anomalies are present in the eastern parts of the Venehaara block. Several ultramafic boulders including mafic metavolcanic rocks and tremolite-serpentine rocks were found (Figure 7.8). Ultramafic rocks in the eastern parts of the Venehaara block differ from the ultramafic rocks in the northern and western side of the block, mainly in terms of the former being more altered and having more massive texture. In this respect, these rocks resemble the cumulate facies rocks in Jänesselkä mafic-ultramafic complex.

Figure 7.8: Outcropped bedrock in a miry terrain (upper photo) in the eastern parts of the Venehaara block. Hand sample of tremolite-serpentine rock (HMHO-2017-38.1; x 7487361, y 593814) from the outcrop (lower photo).

7.2 Petrography

7.2.1 Jänesselkä mafic-ultramafic complex

The most common rock types of ultramafic cumulates of Jänesselkä mafic-ultramafic complex are olivine-serpentine-tremolite-rock (thin section: PSHA-2017-26.1) (Figure 7.9), chlorite-tremolite-serpentine-rock, and serpentinite. These usually show similar mineral assemblages, with only variation in mineral proportions. All the rocks of the Jänesselkä mafic-ultramafic complex have undergone pervasive deformation and metamorphism, and magmatic minerals have not been preserved. Ultramafic cumulates of Jänesselkä have tremolite, serpentine, chlorite, and metamorphic olivine as the main minerals. Tremolite forms randomly oriented acicular stalks that crosscut other main minerals and thus represent retrograde crystallization. These are colorless and clustered and usually form radial aggregates. In places, these textures give the impression of them being the recrystallization products of pyroxene grains. Serpentine has a bladed form and is intergrown with chlorite in the groundmass. Serpentine is often clustered around remnants of olivine. Chlorite appears as blueish to greenish pleochroic slabs and is the main cleavage-forming mineral. Olivine is heavily altered and found as anhedral grains with characteristic irregular cleavage. Olivine is associated with serpentine, magnetite and iddingsite. Magnetite is a common accessory mineral and is most abundant around serpentine and olivine. Some sulfides have also been recorded from these rocks (Figure 7.11), pyrrhotite being the most abundant.

The suggested non-cumulus komatiites of Jänesselkä are dominated by chlorite and tremolite. In addition, serpentine is found as a major mineral. Olivine is rather uncommon, however, accumulations of serpentine and magnetite after olivine are abundant. Except for grains being often smaller and cleavage controlling their orientation, tremolite appears in similar fashion as in the ultramafic cumulates described above. Serpentine and chlorite are the main groundmass minerals. The most common accessory minerals are talc and magnetite. Non-cumulus ultramafic rocks of the Jänesselkä mafic-ultramafic complex are often fine-grained and show a strong cleavage, with crenulation cleavage in the most heavily deformed rocks (thin section: PSHA-2017-27.1) (Figure 7.10). The majority of these rocks are tremolite-chlorite schists, talc-tremolite-chlorite schists and serpentine-tremolite rocks.

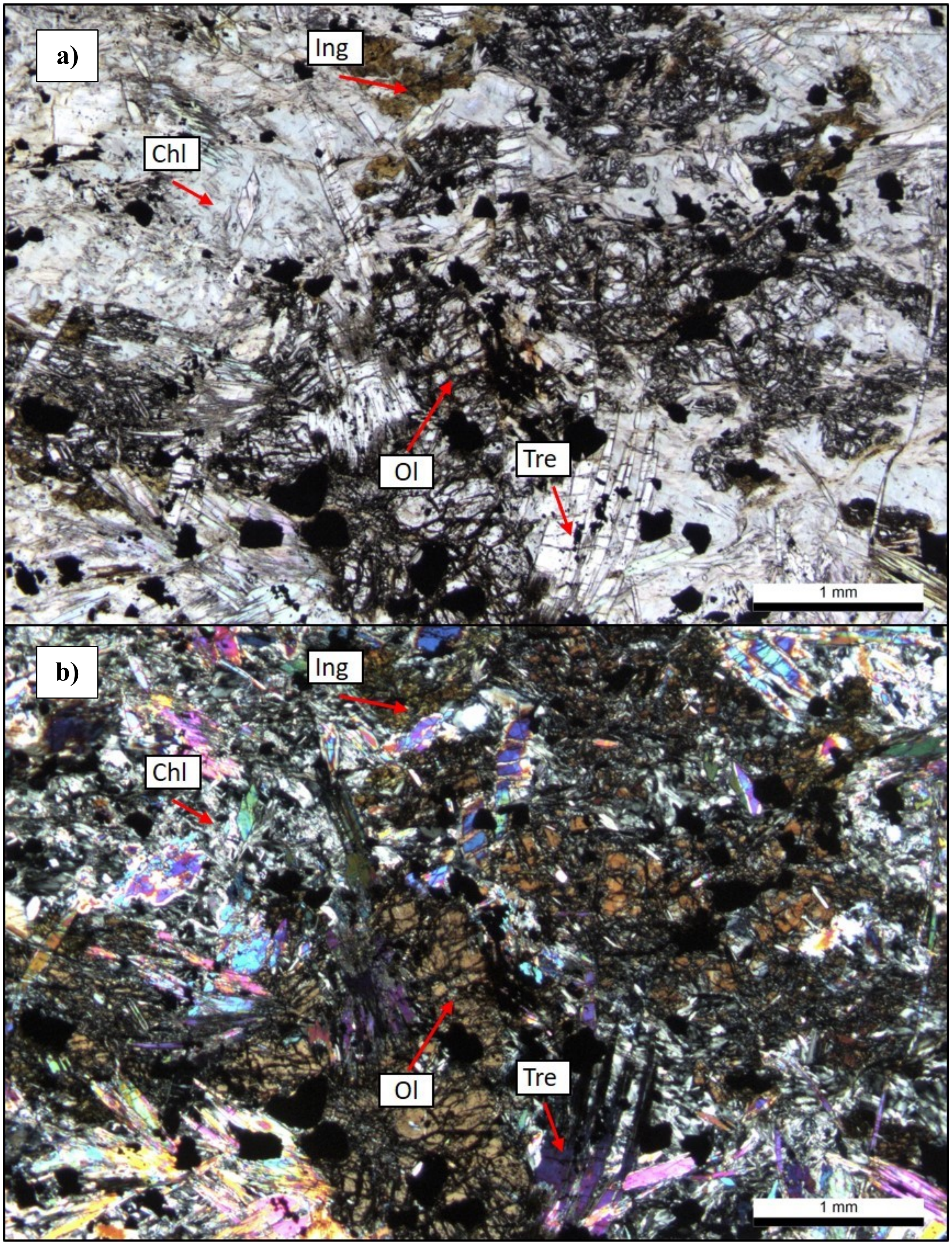

Figure 7.9: Olivine-chlorite-tremolite rock (PSHA-2017-26.1) from the Jänesselkä mafic-ultramafic complex in plane-polarized light (a) and cross-polarized light (b). Serpentine appears as a groundmass mineral with chlorite. Abbreviations for minerals: Ol – olivine, Tre – tremolite, Chl – chlorite, Ing – Iddingsite.

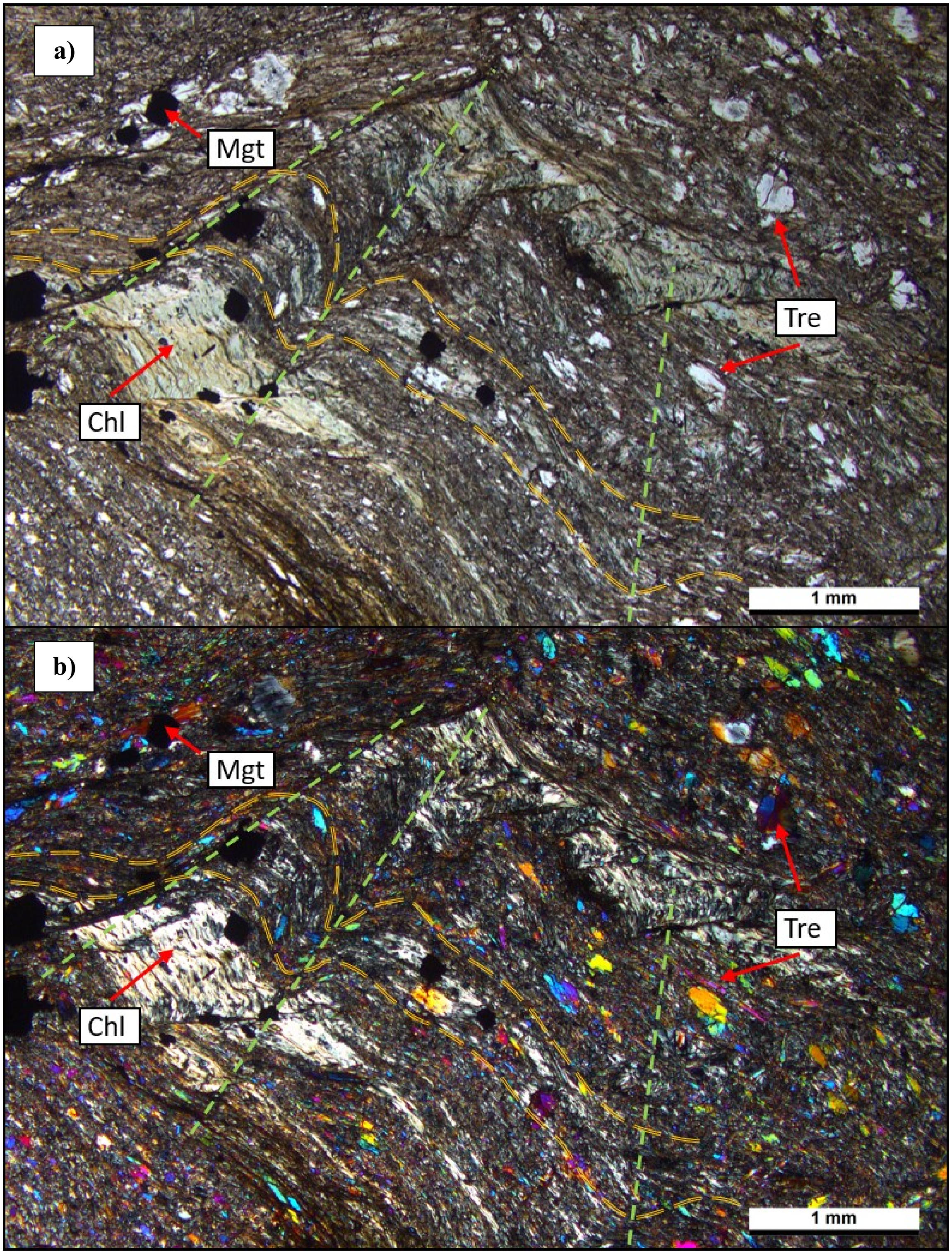

Figure 7.10: Chlorite-tremolite schist (PSHA-2017-27.1) from the Jänesselkä mafic-ultramafic complex in straight polarized light (a) and cross polarized light (b). Area visible in the figure represents the fold hinge. Prevailing cleavage is marked with orange dashed lines. A spaced crenulation cleavage is visible, where crenulation domains are marked with green dashed lines. Abbreviations for minerals: Tre – tremolite, Chl – chlorite, Mgt – magnetite.

The gabbroic rocks of the Jänesselkä mafic-ultramafic complex are amphibole-rich (thin section: JHTE-2017-35.2) (Figure 7.12). Quartz and plagioclase are the main groundmass minerals and have recrystallized habitus. Amphibole crosscuts other major minerals as porphyroblasts, and has formed retrogradely. Apatite and rutile appear as accessory minerals.

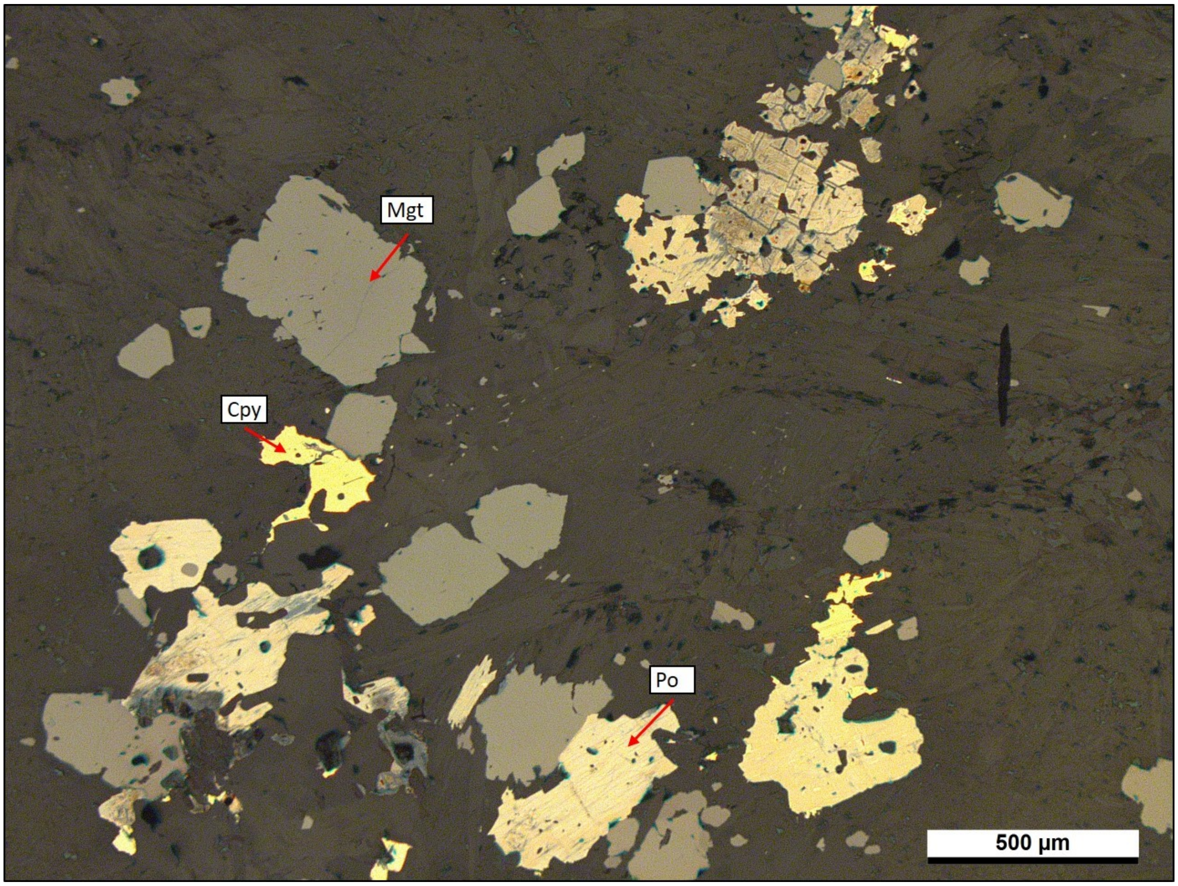

Figure 7.11: Sulfides and oxides in the tremolite-serpentine rock (PSHA-2017-20.1) in the Jänesselkä mafic-ultramafic complex. Mineral abbrevations: Cpy - chalcopyrite, Po - pyrrhotite, Mgt – magnetite.

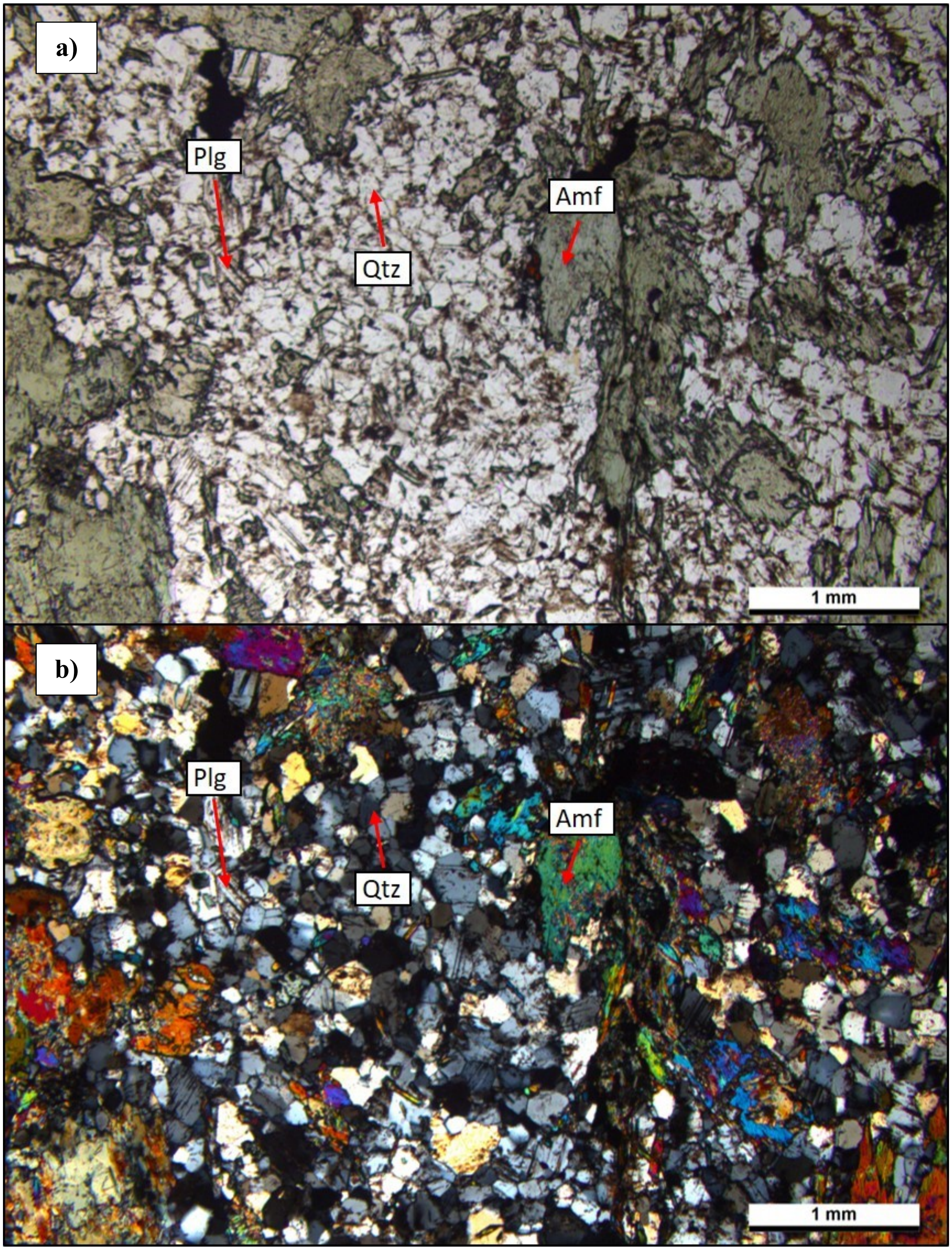

Figure 7.12: Leucogabbro (JHTE-2017-35.2) from the Jänesselkä mafic-ultramafic complex in straight polarized light (a) and cross polarized light (b). Quartz- and feldspar-dominated zone is visible in the center of the figures. Amphibole porphyroblasts show tattered and irregular crystal shape. Abbreviations for minerals: Qtz – quartz, Plg – plagioclase, Amf - amphibole

7.2.2 Tulppio ultramafic complex

Samples from the Tulppio ultramafic complex are from an exploration project carried out by the GTK in 2005–2008 (Heikura et al., 2010). All examined rock types are from drill cores, with the sample name referring to core number and depth of the sample. In this study, three rock types are examined, from an unaltered dunitic core to its moderately metamorphosed equivalent to completely metamorphosed margins of the dunitic body.

The core of the Tulppio ultramafic body has a mineral assemblage of magmatic olivine with cotectic spinel group minerals found at olivine grain boundaries (thin section: R318@15.70)(Figure 7.13). Olivine, in terms of grain size, is bimodal. In plane-polarized light, olivine is tender grey, as the result of magnetite extraction from the olivine in anhydrous metamorphic circumstances. Chromite is subhedral to euhedral with some grains mantled by magnetite that replaced the primary chromite. Magnetite margins on chromites are the thickest around the most serpentinized olivines. In some instances chromite has been replaced by magnetite completely. The amount of magnetite replacing chromite can be used as an estimate of the degree of metamorphism (Barnes et al., 1996).

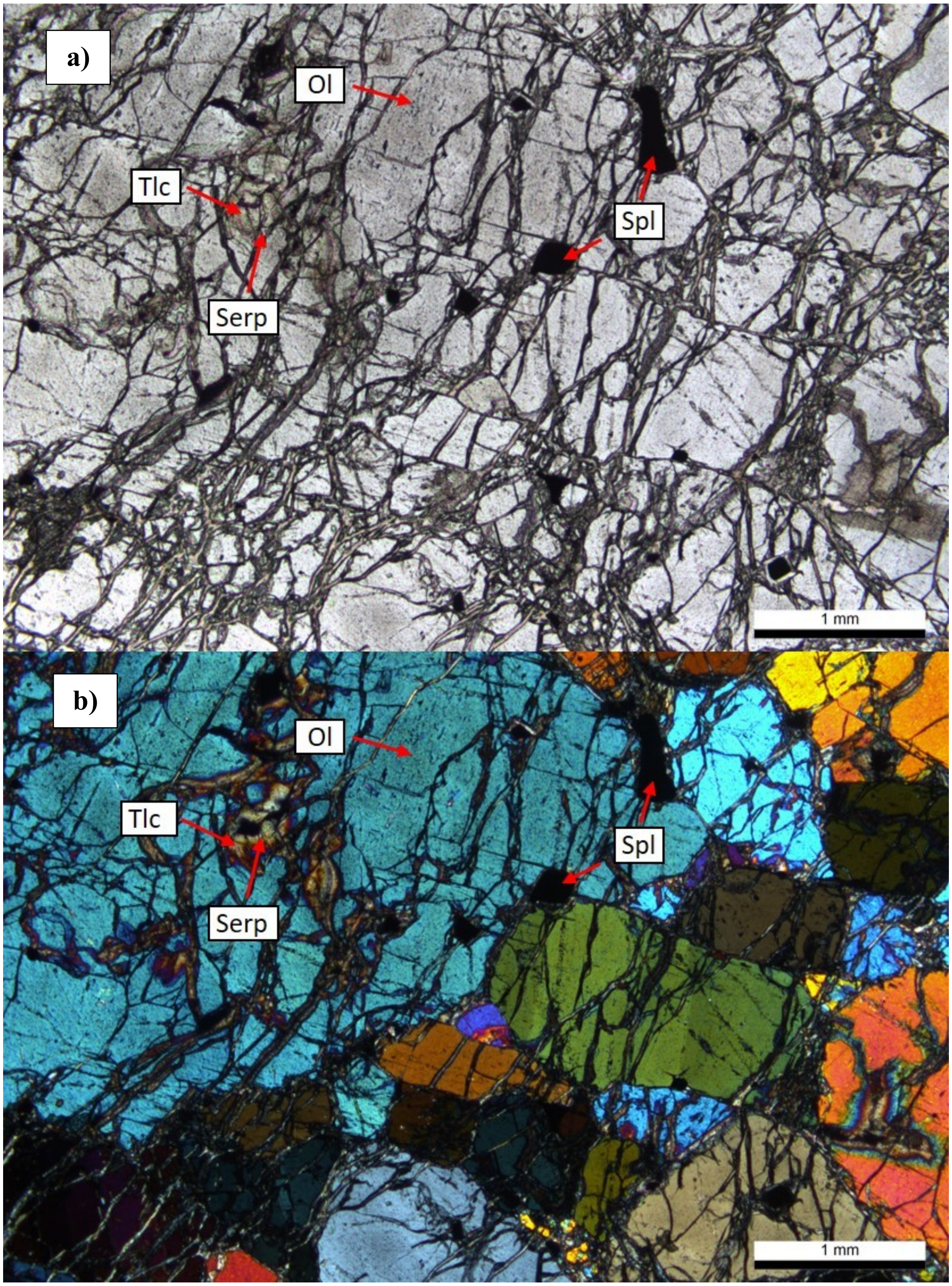

Figure 7.13: Dunite (R318@15.70) from the least altered part of the Tulppio ultramafic complex in straight polarized light (a) and cross polarized light (b). Olivine (Ol) shows a clear bimodal grain size distribution, whereas chromite and magnetite (Spl) appear at the grain boundaries. Slight serpentinization (Serp) is visible with accessory talc (Tlc) around the cleavage fractures that crosscut olivine.

An interesting altered rock type in the Tulppio ultramafic complex is a talc-chlorite-olivine rock also referred to as "black dunite" (Figures 7.14 and 7.15) (thin section: R319@158.15) (Heikura et al., 2010). It consists of large, randomly oriented, multiple centimeters long metamorphic olivine blocks. Chlorite and talc appear as large flakes between olivine grains. Carbonate and spinel group minerals are as accessory minerals. The former is found as fracture fills, the latter appear often as accumulations at the olivine grain margins.

Figure 7.14: Drill core (R319@158.15) consisting of talc-carbonate-olivine rock, (black dunite) from the Tulppio ultramafic complex. Dark grains are metamorphic olivine and pale colored areas talc and carbonate. Picture from Heikura et al. (2010).

Towards the margins of the dunitic body, alteration intensifies, and serpentine dominates. Olivine is almost completely dissipated and, in places, only accumulations of serpentine and magnetite after olivine are visible. These rocks (thin section: R318@26.75) (Figure 7.16) show signs of deformation with slight banding often present. Fractures are common and often filled by carbonate. Rocks forming the margins of the dunitic body are dominantly fine-grained serpentinites and olivine-serpentine rocks.

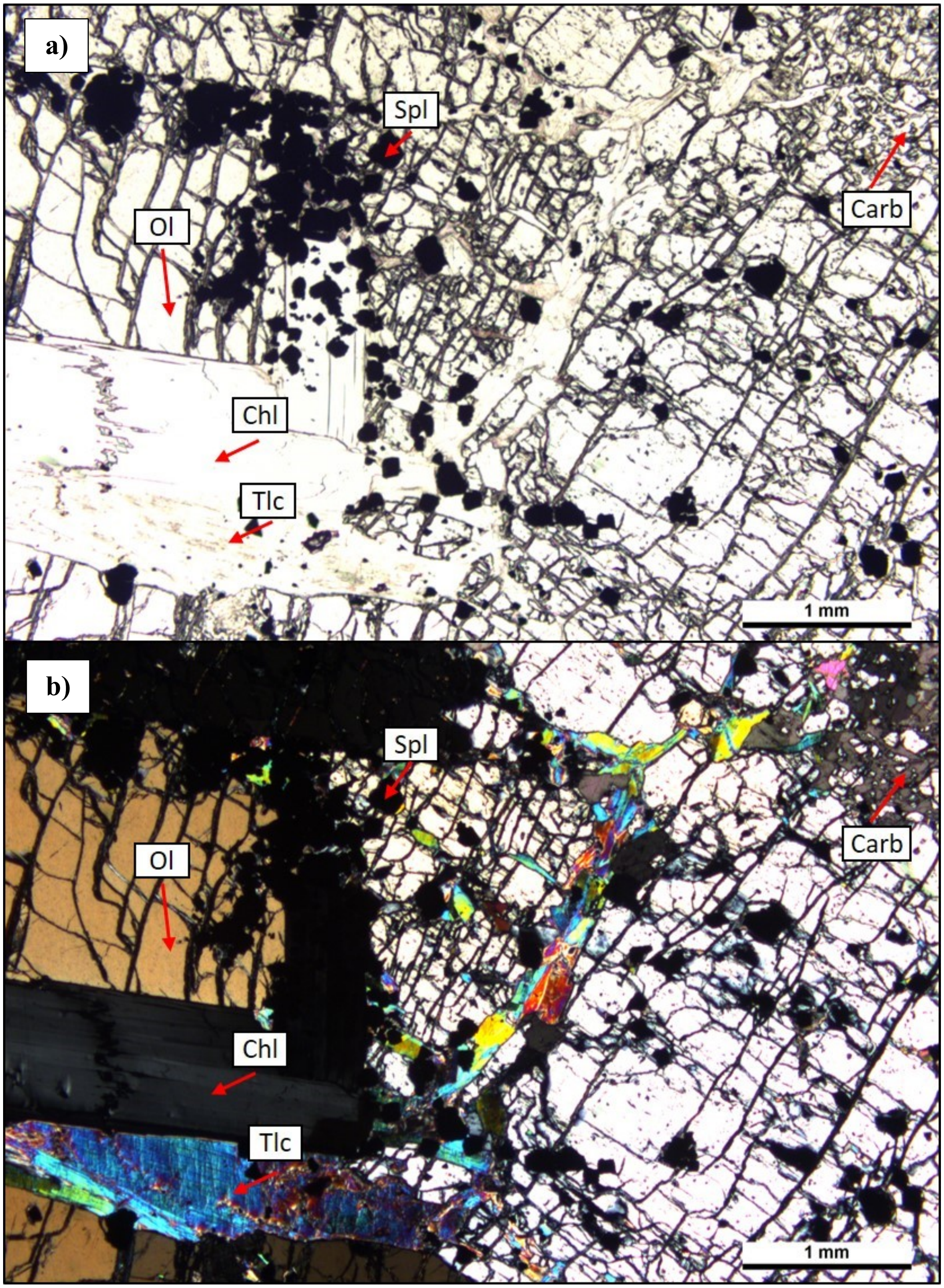

Figure 7.15: Talc-chlorite-olivine rock (R319@158.15) from the Tulppio ultramafic complex in straight polarized light (a) and cross polarized light (b). Olivine (Ol) appears as large metamorphic blocks. Chlorite (Chl) and talc (Tlc) are other two main minerals.

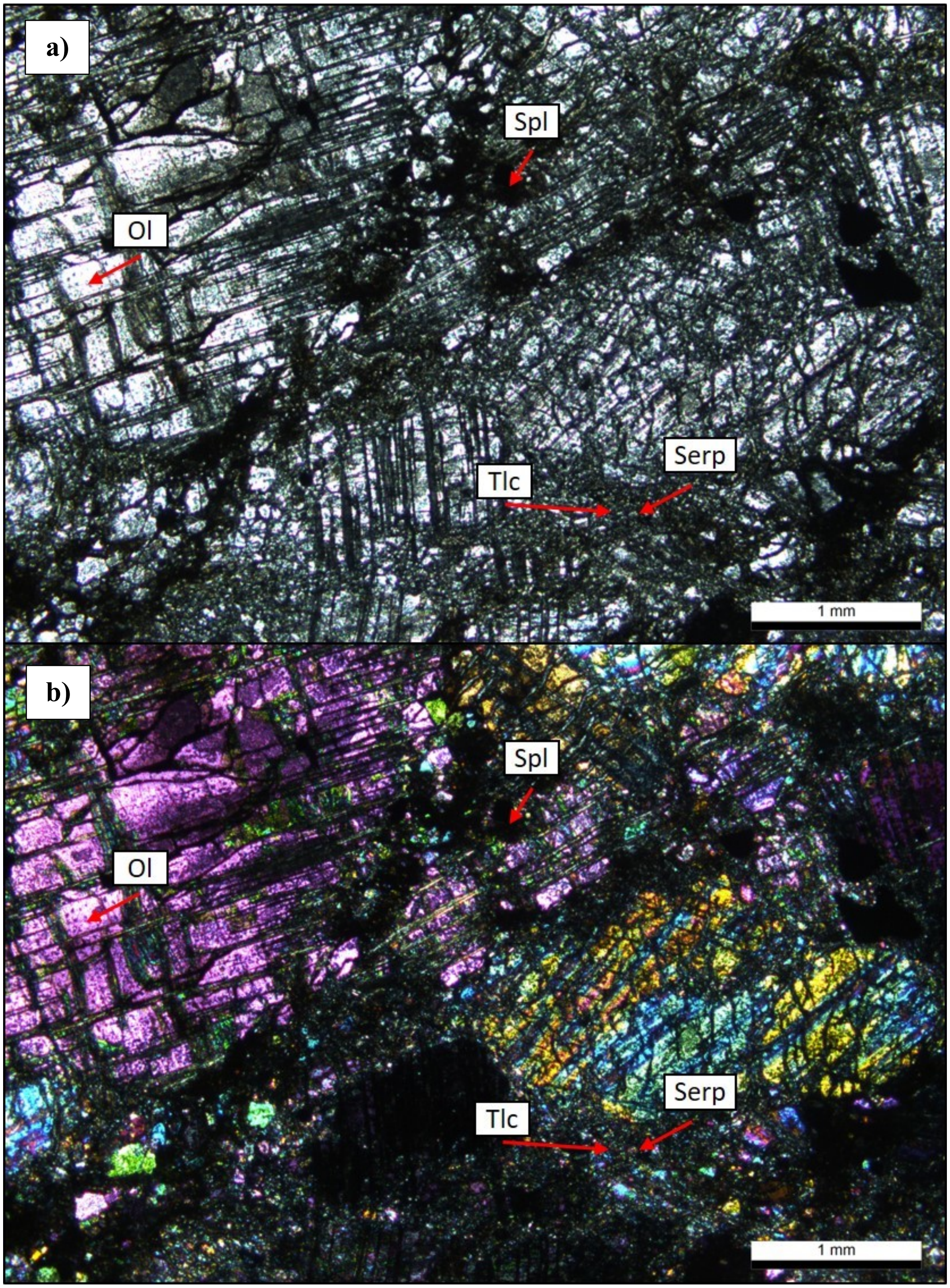

Figure 7.16: Olivine-serpentine rock (R318@26.75) in the Tulppio ultramafic complex in straight polarized light (a) and cross polarized light (b). Altered olivine grains are prismatic by their crystal shape, thus they are interpreted to be metamorphic. Abbreviations for minerals: Ol - olivine, Serp – serpentine, Spl - spinel, Tlc – talc.

7.2.3 Värriöjoki ultramafic complex

The samples examined from the Värriöjoki ultramafic complex originate from an exploration project by the Geological Survey of Finland (Törmänen et al., 2007) and field studies carried out by the author and the research team. Excluding the olivine adcumulate from the Venehaara block, samples described are from drill cores. Thin sections are presented in a sequence from magmatic dunite from central parts of the Venehaara block, to the serpentinites and metaperidotites at the margins of the complex. The latter is recorded only from the Värriöjoki main block.

The dominant rock type in the Värriöjoki ultramafic complex is dunite (thin section: JHTE-2017-25.2) (Figure 7.17). Primary cumulus textures are well preserved and found from all of the four bodies forming the complex. In these rocks, olivine has a bimodal grain size distribution. Similar to the magmatic olivine of Tulppio ultramafic complex, the one in Värriöjoki is greyish to brownish. In places, tremolite appears as small acicular crystals that replace other minerals. Spinel group minerals appear at olivine grain margins and they are dominantly chromite with magnetite margins. Magnetite margins on chromite are relatively thin, with little evidence of post-magmatic replacement of chromite by magnetite. Clinopyroxene can also be found as an accessory mineral.

As the alteration and deformation are stronger towards the margins of the ultramafic bodies, serpentine starts to dominate over olivine (thin sections: R20@192.45, R10@121.55) (Figures 7.18 and 7.19). Whether the remaining olivine is magmatic or recrystallized is hard to say, because of pervasive deformation and alteration. However, olivine appearing colorless in plane-polarized light and, in places, its angular habitus gives an impression of olivine having a metamorphic origin. Overall, all olivine grains are heavily fractured, and talc, carbonate, and serpentine appear as common minerals as fracture fillings.

Altered olivine orthocumulates in Värriöjoki are found in the contact with the gneisses surrounding the ultramafic body and are in places associated with gabbroic rocks. The main minerals in the examined altered olivine orthocumulate (thin section: R10@196.35) (Figure 7.20) are olivine, pyroxene and tremolite. Olivine and pyroxene are almost completely altered to serpentine and amphibole, and tremolite appears as metamorphic crystals replacing other minerals. Chlorite, and iddingsite are also found, the former in the groundmass.

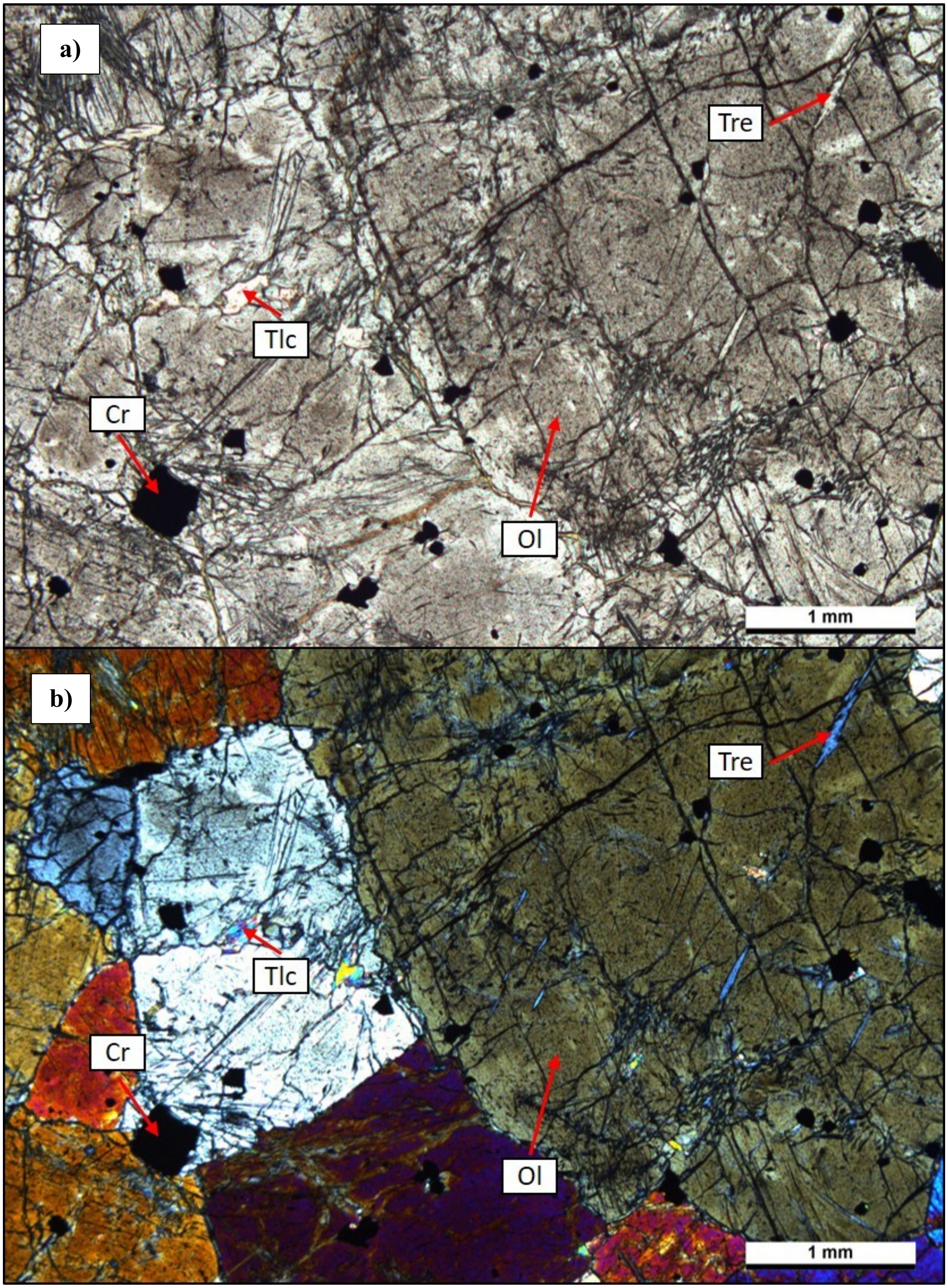

Figure 7.17: Dunite (JHTE-2017-25.2) from the Venehaara block of the Värriöjoki ultramafic complex in straight polarized light (a) and cross polarized light (b). Tremolite (Tre), talc (Tlc) and, chromite (Cr) appear as accessory minerals. Chromite is cotectic with olivine (Ol), tremolite and talc are metamorphic.

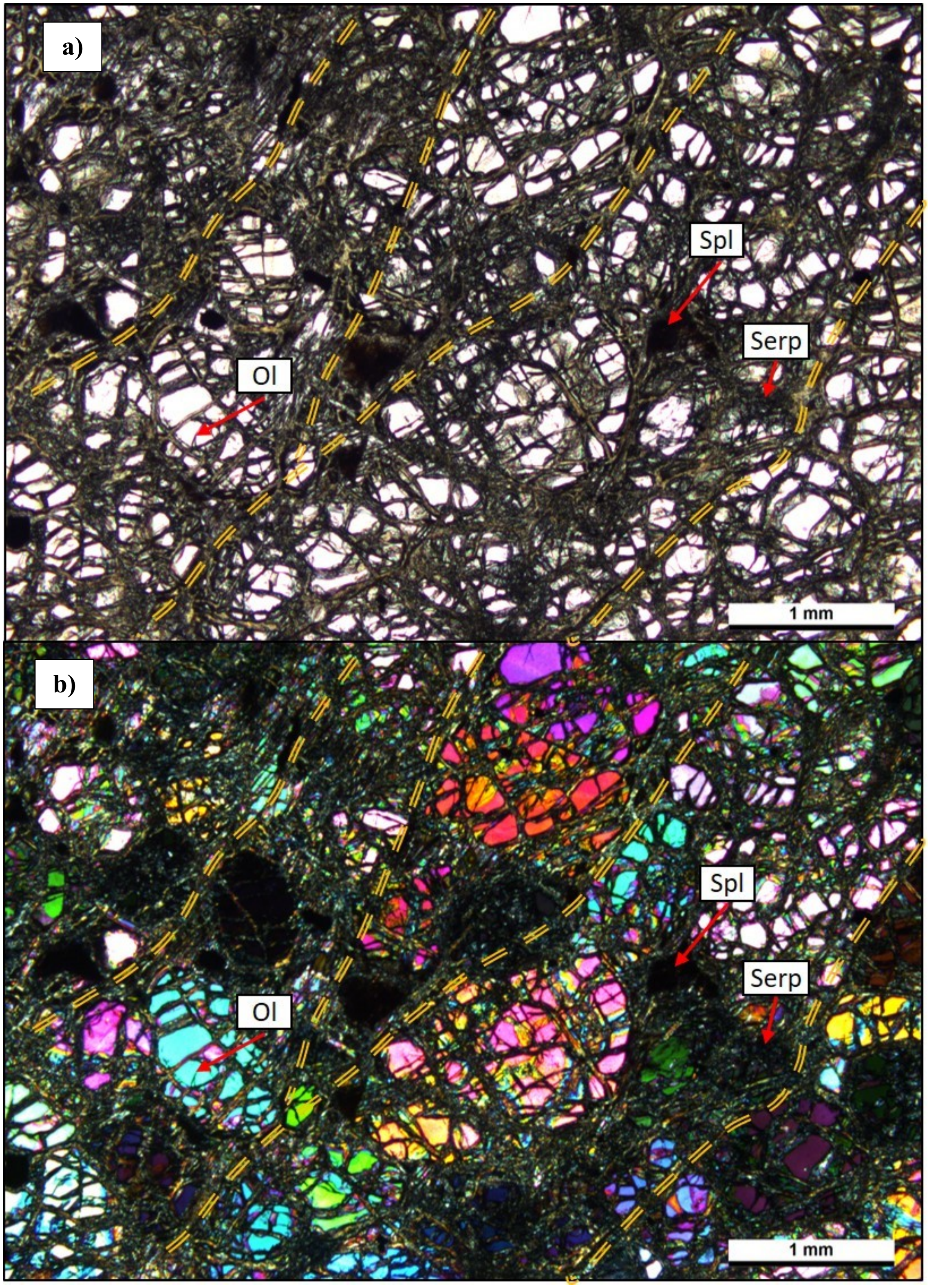

Figure 7.18: Olivine-serpentine rock (R20@192.45) from the Värriöjoki block of the Värriöjoki ultramafic complex in straight polarized light (a) and cross polarized light (b). Prevailing cleavage representing deformation is marked with orange dashed lines. Mineral abbreviations: Ol – olivine, Spl – spinel, Serp – serpentine.

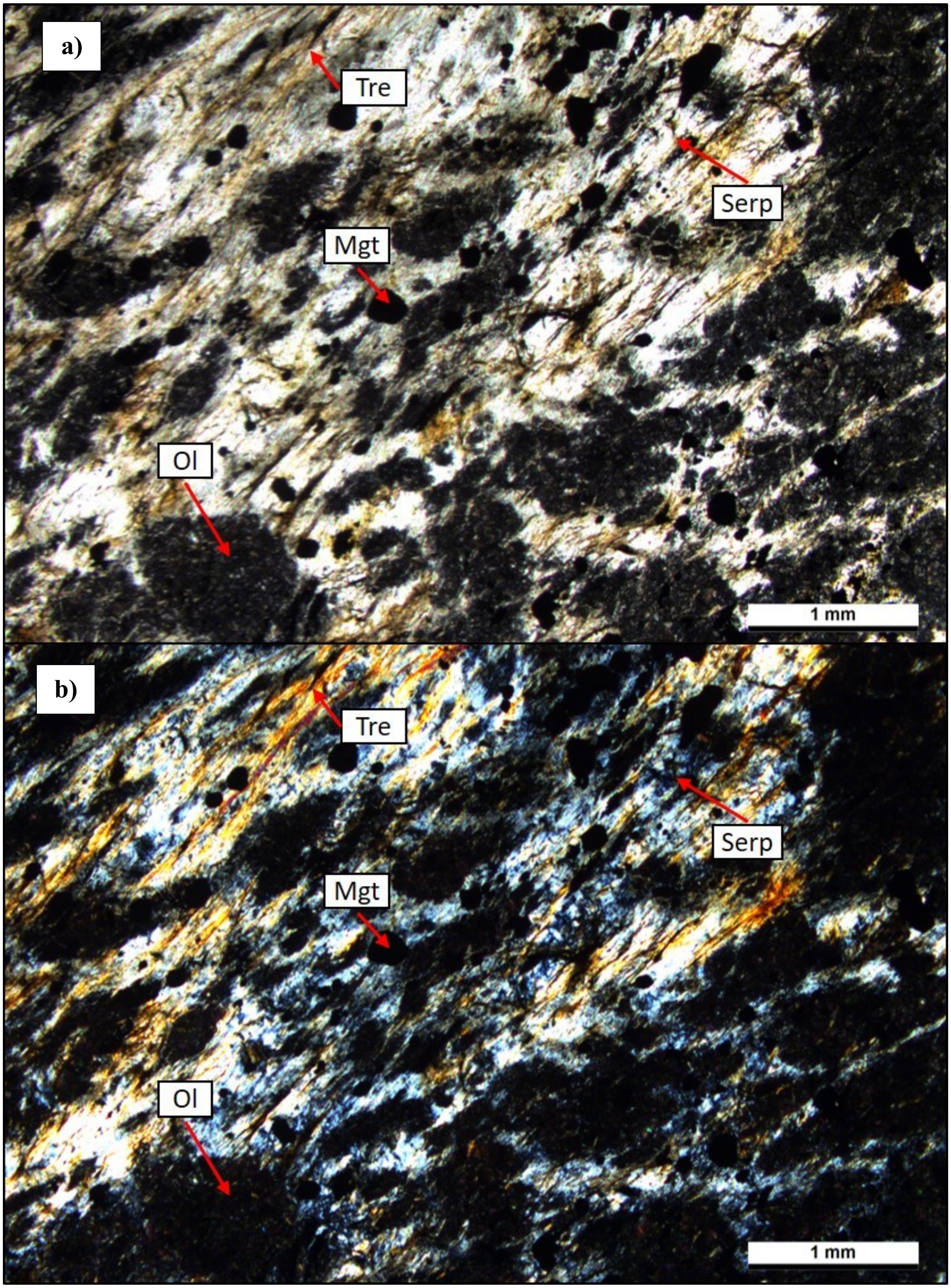

Figure 7.19: Pervasively deformed serpentinite (R10@121.55) from the Värriöjoki ultramafic complex in straight polarized light (a) and cross polarized light (b). Mineral abbreviations: Ol – Olivine, Mgt – magnetite, Serp – serpentine, Tre – tremolite.

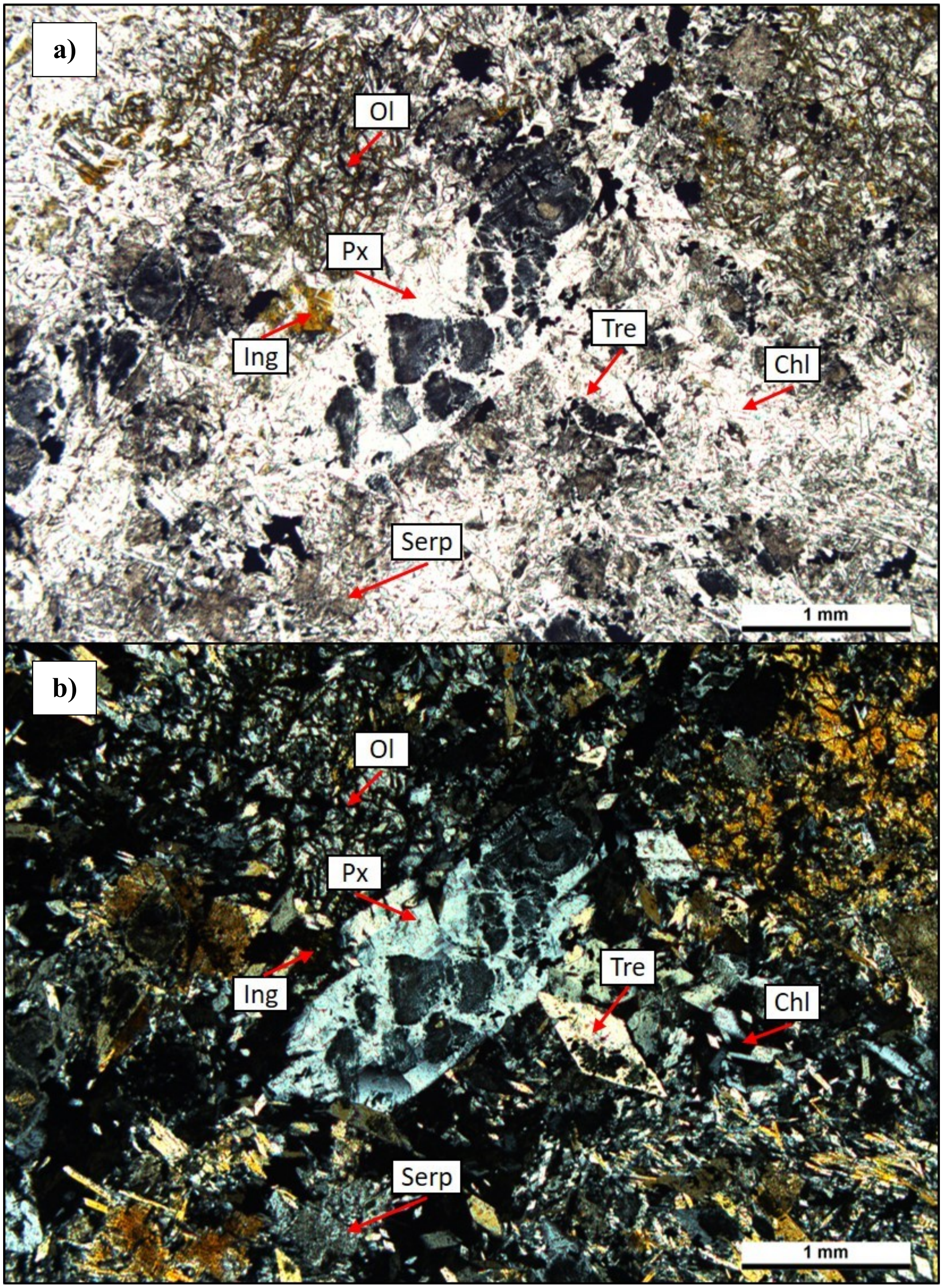

Figure 7.20: Metaperidotite (R10@196.35) from the Värriöjoki ultramafic complex in straight polarized light (a) and cross polarized light (b). Sample represents a rock unit in the 40 m-thick altered marginal zone in the contact with gneisseis surrounding the ultramafic complex. Mineral abbreviations: Ol - olivine, Px - pyroxene, Chl - chlorite, Serp – serpentine, Ing – iddingsite, Tre – tremolite.

7.3 Geochemistry

The dataset complied from the pre-existing and new analytical data, was used to study the geochemistry of the target sites. This included 80 samples from the Jänesselkä ultramafic complex, 75 of which were of ultramafic composition. Five samples were from gabbroic rocks. 100 komatiitic samples from Tulppio and 233 komatiitic samples from Värriöjoki (153 samples from the Värriöjoki block, 17 from the Liessijoki block, 47 samples from the Leppäselkä block, and 16 samples from the Venehaara block) were also included in the dataset.

7.3.1 Jänesselkä mafic-ultramafic complex

The ultramafic rocks of the Jänesselkä mafic-ultramafic complex contain, on average, 27.6 wt.% MgO and 48.0 wt.% SiO_2. The gabbroic rocks of Jänesselkä contain 4.6–9.2 wt.% MgO and 47.9–56.1 wt.% SiO_2 and ultramafic rocks contain 16.6–32.1 wt. % MgO and 43.3–52.2 wt. % SiO_2. A possibly post magmatic enrichment in SiO_2 can be identified at 25–32 wt.% MgO (Figure 7.21). In the Jänesselkä mafic-ultramafic complex, rocks with the highest MgO contents are most abundant in the northern parts of the complex, in the area of the strongest magnetic anomaly.

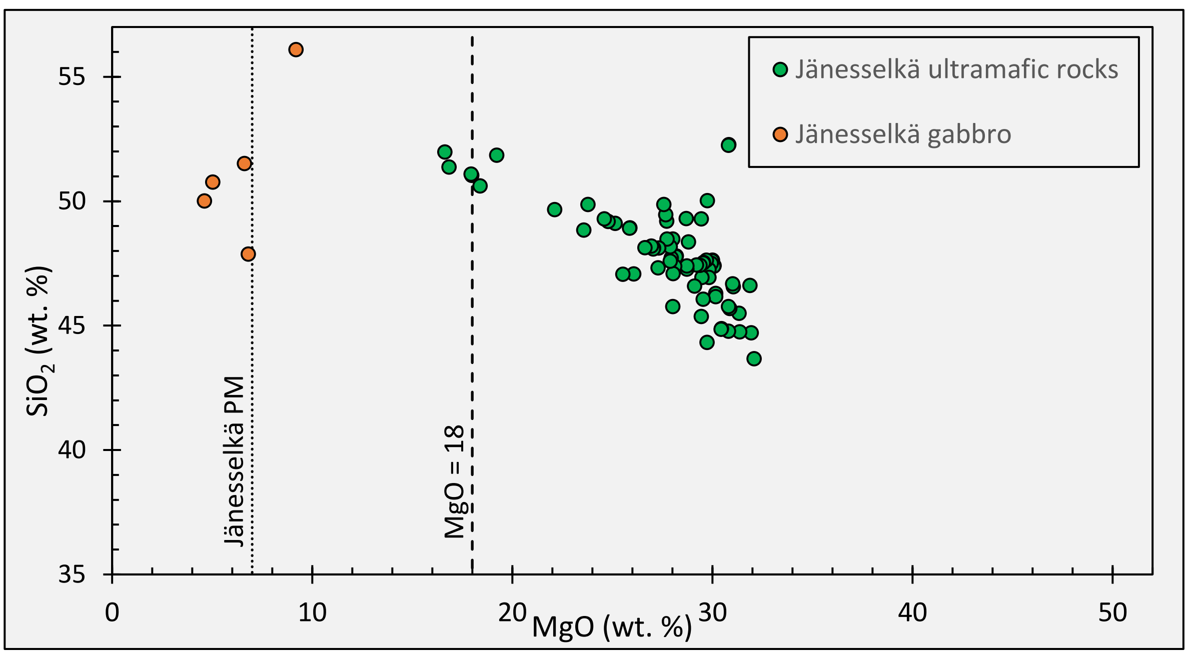

Figure 7.21: Compositions of the rocks of the Jänesselkä mafic-ultramafic complex shown in a MgO vs. SiO_2 plot. Dotted and dashed lines are estimation of parental magma (PM) MgO content for the Jänesselkä mafic-ultramafic complex (see Section 8.1) and the minimum MgO content of komatiites (see Le Bas, 2000).

The Al content of the mafic-ultramafic rocks of Jänesselkä rages from 5.3 to 20.8 wt. % with the highest value in a sample from a leucogabbro in the central parts of the Jänesselkä mafic-ultramafic complex (Figure 7.22). Average Al_2O_3 value is 17.8 wt. % for gabbroic rocks and 7.1 wt. % for ultramafic rocks. Aluminum content seems to conform to an olivine fractionation trend with off-trend samples representing the most metamorphosed samples.

The ultramafic rocks of Jänesselkä show poor correlation of TiO_2 with MgO with considerable scatter seen at all MgO values. TiO_2 contents range from 0.14 to 1.17 wt.% with the highest values obtained from a mafic volcanic rock at the southern contact of the complex (Figure 7.23). Average TiO_2 value is 0.8 wt. % for gabbroic rocks and 0.3 wt. % for komatiitic rocks.

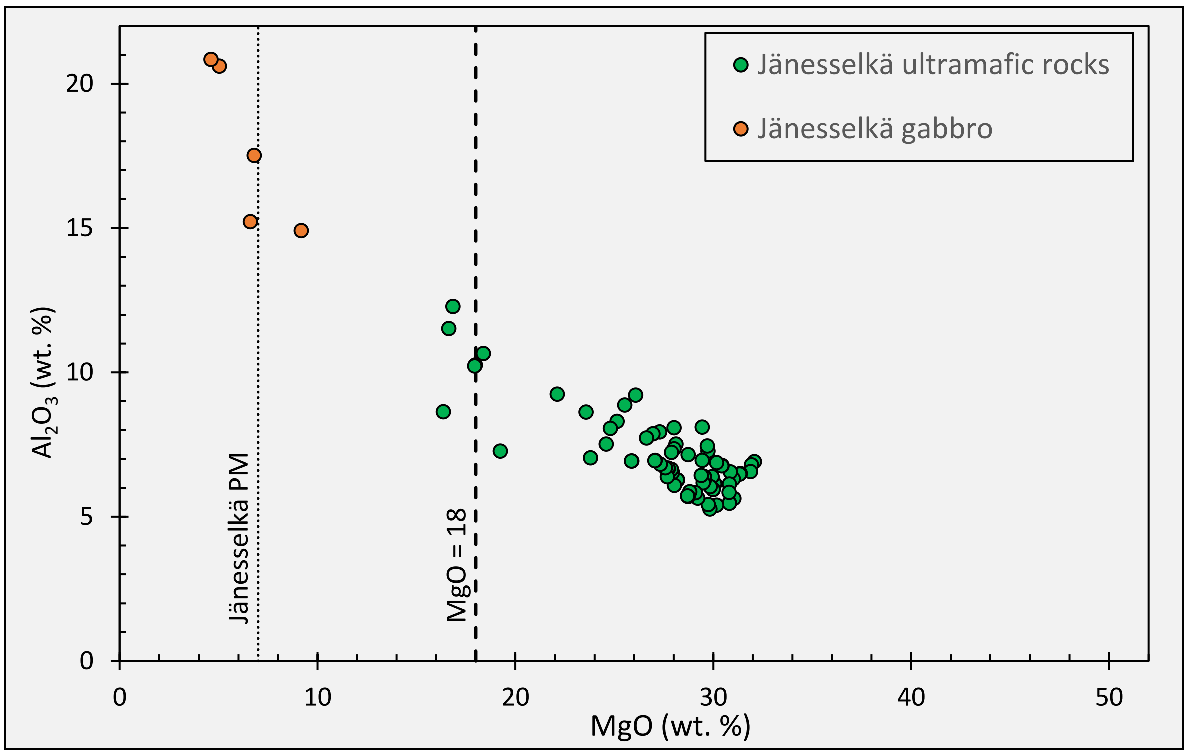

Figure 7.22: Compositions of the rocks of the Jänesselkä mafic-ultramafic complex shown in a MgO vs. Al_2O_3 plot. Samples with the highest aluminum content represent the gabbroic rocks in the central parts of the complex. Dotted line is the estimation of the parental magma (PM) MgO content for the Jänesselkä mafic-ultramafic complex (see Section 8.1) and dashed line is the minimum MgO content of komatiites (see Le Bas, 2000).

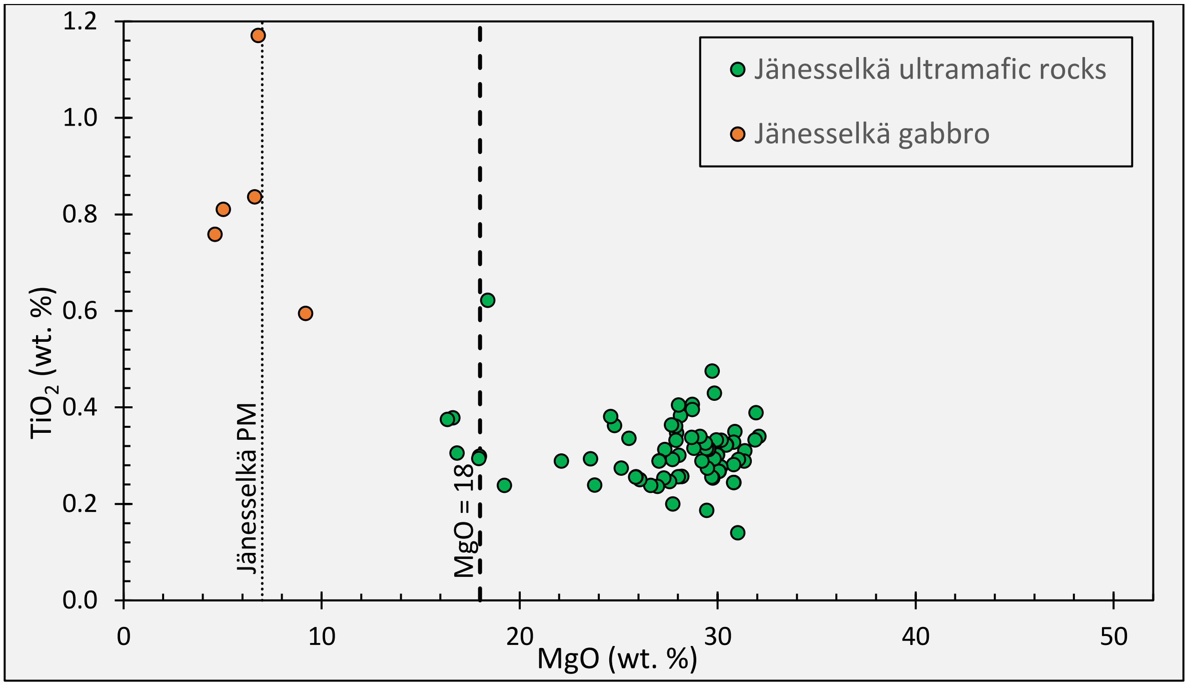

Figure 7.23: Compositions of the rocks of the Jänesselkä mafic-ultramafic complex shown in a MgO vs. TiO_2 plot. Dotted and dashed lines are estimation of parental magma (PM) MgO content for the Jänesselkä mafic-ultramafic complex (see Section 8.1) and the minimum MgO content of komatiites (see Le Bas, 2000).

The majority of ultramafic rocks analyzed from the Jänesselkä complex are AUK type with only two samples showing ADK values (Figure 7.24). The median Al_2O_3/TiO_2-value for komatiitic rocks in the Jänesselkä complex is 21. The gabbroic rocks of Jänesselkä have Al_2O_3/TiO_2-values ranging from 15 to 27 (22 on average).

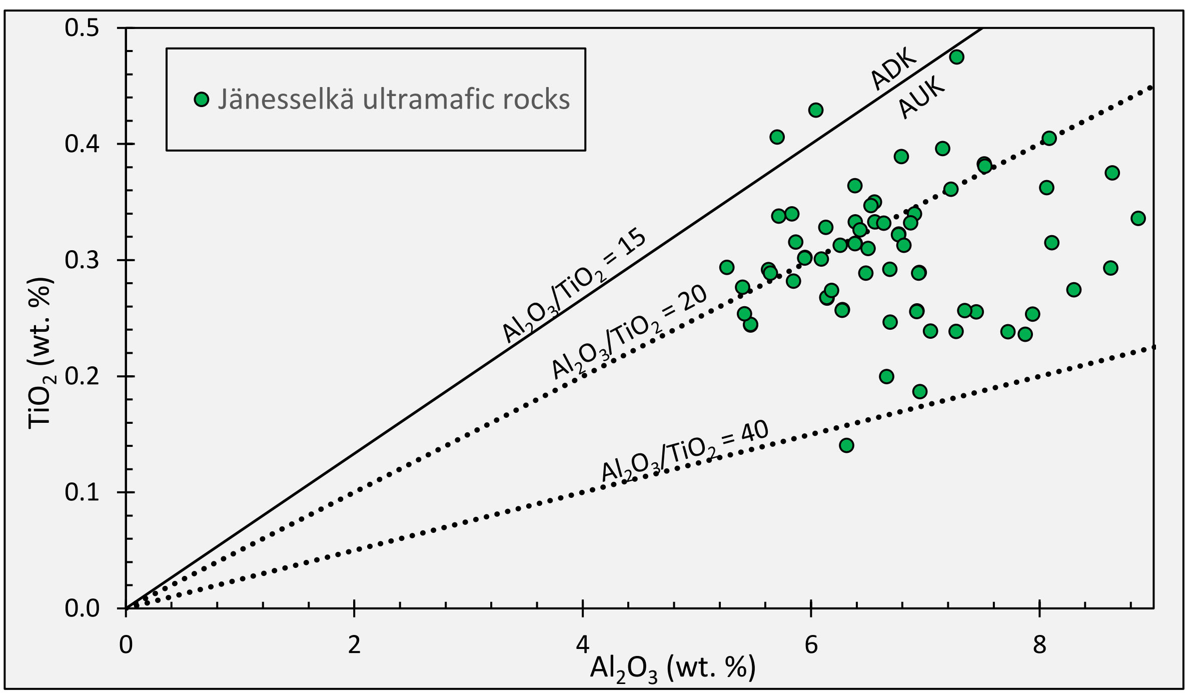

Figure 7.24: The ultramafic rocks of Jänesselkä shown on Al_2O_3 vs. TiO_2 plot. The solid line illustrates the classification of komatiitic rocks into ADKs (Al_2O_3/TiO_2 < 15) and AUKs (Al_2O_3/TiO_2 > 15) (cf. Section 2.3).

The ultramafic rocks of Jänesselkä show slightly depleted Ni contents compared to typical values produced by fractionation of komatiitic magma (Makkonen et al., 2017) (Figure 7.25). With 0.06–0.2 wt.% Ni, they form a well-defined trend controlled by olivine. However, a slight scatter is evident especially at 25–31 wt.% MgO. Several rocks with less than18 wt. % of MgO show strong enrichment in Ni, with the overall trend of these rocks following the fractionation trend of komatiitic magmas.

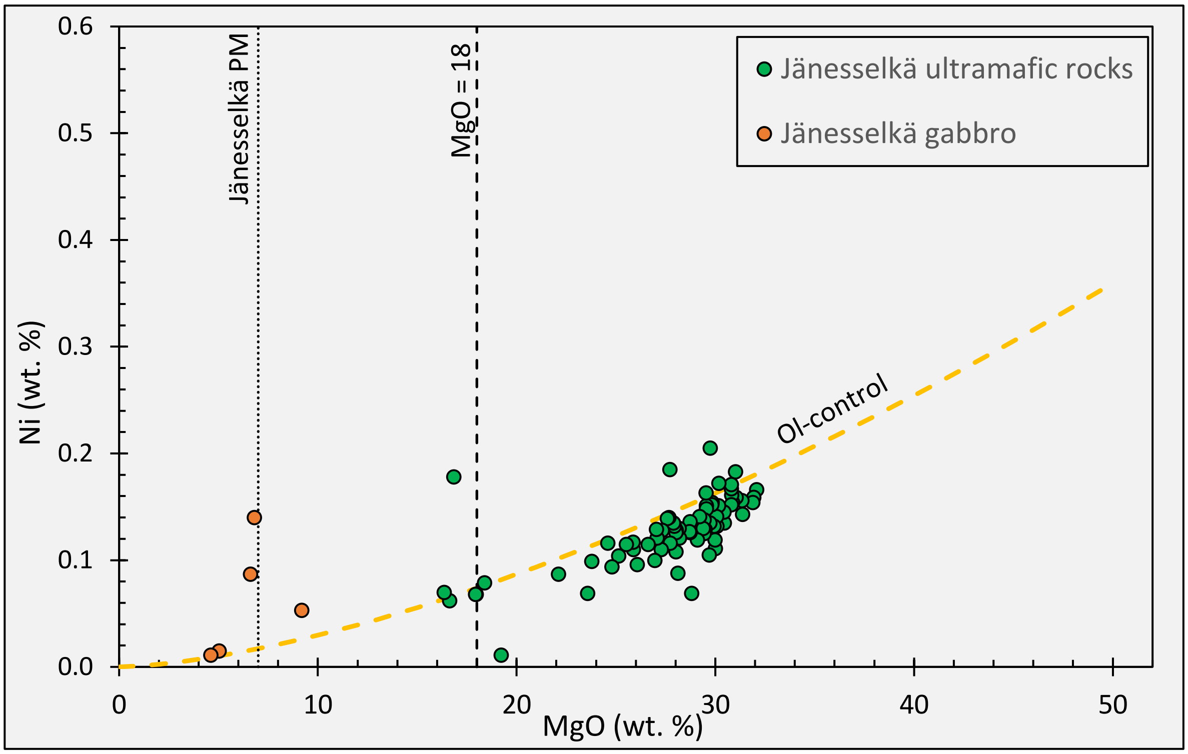

Figure 7.25: Compositions of the rocks of the Jänesselkä mafic-ultramafic complex shown in a MgO vs Ni. Yellow dashed line represents the typical Ni content in komatiites in olivine-controlled fractionation (Makkonen et al., 2017). Dotted line is the estimation of the parental magma (PM) MgO content for the Jänesselkä mafic-ultramafic complex (see Section 8.1) and dashed line is the minimum MgO content of komatiites (see Le Bas, 2000).

In terms of Cr, the majority rocks analyzed from Jänesselkä form a coherent population, with linear positive correlation to MgO (Figure 7.26). Cr values of the ultramafic rocks (0.15–0.89 wt. %) are similar to typical rocks formed from komatiitic magmas (Barnes, 1998). Several off-trend samples are observed with highest Cr content being 0.9 wt.%. Non-komatiitic compositions have Cr contents of 0.03 – 0.07 wt. %.

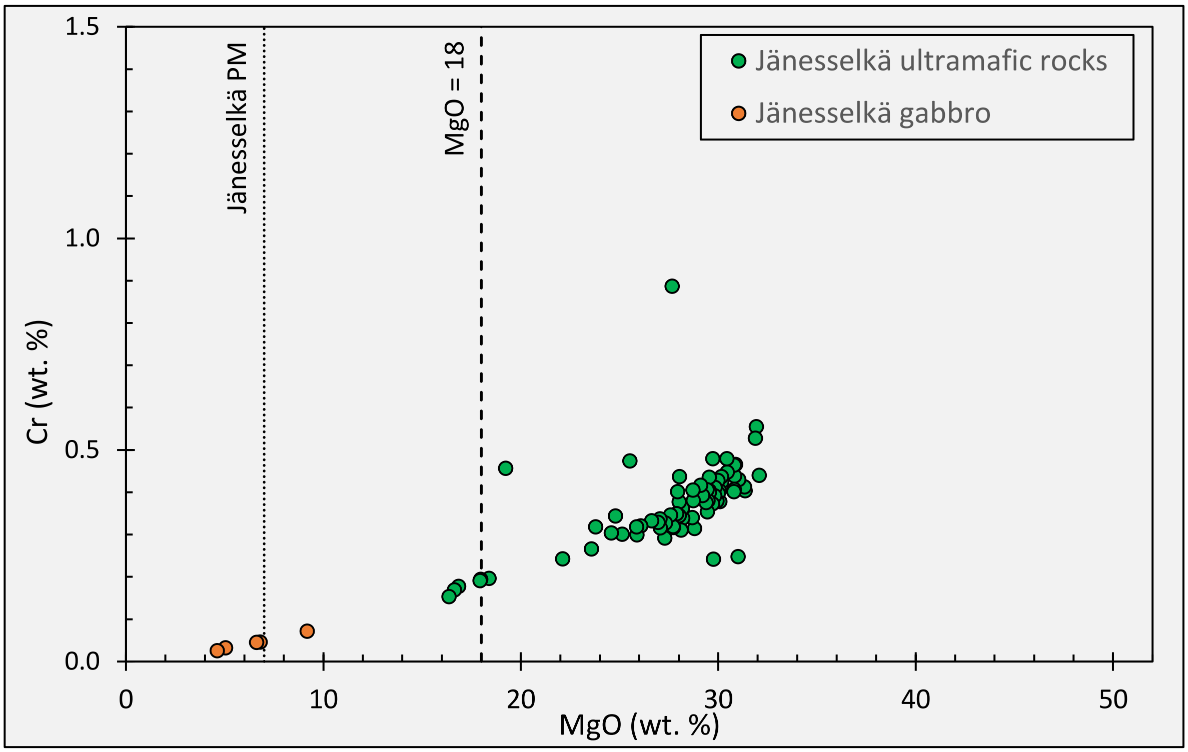

Figure 7.26: Compositions of the rocks of the Jänesselkä mafic-ultramafic complex shown in a MgO vs Cr plot. Dotted line is the estimation of the parental magma (PM) MgO content for the Jänesselkä mafic-ultramafic complex (see Section 8.1) and dashed line is the minimum MgO content of komatiites (see Le Bas, 2000).

On the basis of their REE content, the ultramafic rocks of Jänesselkä show relatively large concentrations of LREE (Figure 7.27) with notable scatter being observed especially for La. It shows values ranging from 1 to 37 times chondritic values (McDonough & Sun, 1995). Corresponding values for Lu range from 4 to 10 with HREE values of all ultramafic samples forming rather flat and uniform patterns. Also, a distinct negative Eu anomaly can be observed in most of the komatiitic samples, this being strongest for the samples with the highest LREE values. Negative Eu anomaly can not be seen for the one gabbroic sample.

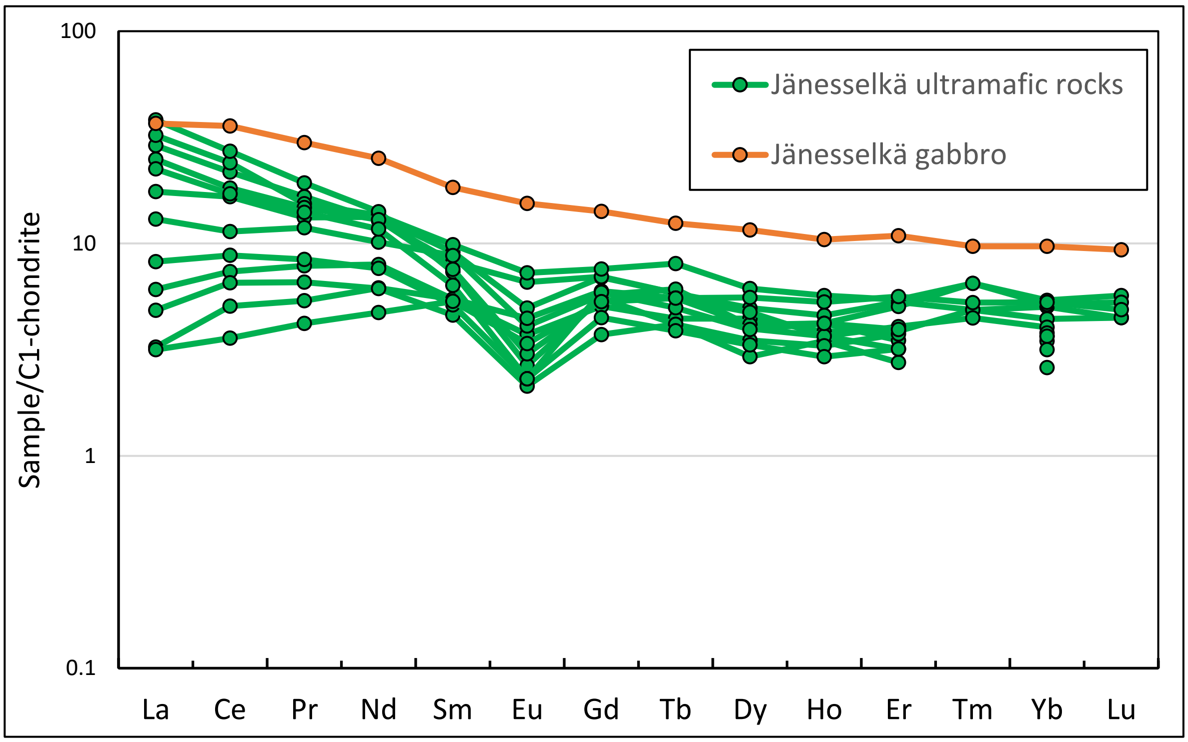

Figure 7.27: C1-chondrite normalized (McDonough & Sun, 1995) REE plot of the rocks forming the Jänesselkä mafic-ultramafic complex. Sample with the most elevated values represents the gabbro from the central parts of the complex (JHTE-2017-35.2) from the central parts of the complex.

7.3.2 Tulppio ultramafic complex

Komatiitic olivine cumulates dominate the lithology of the Tulppio ultramafic complex. The majority of the analyzed samples have a MgO content greater than 28 wt.%, with a main population at 40–50 wt.% MgO (Figure 7.28). These are olivine meso- to adcumulates and their metamorphosed equivalents, with the scatter in SiO_2 content most likely due to post-magmatic processes.

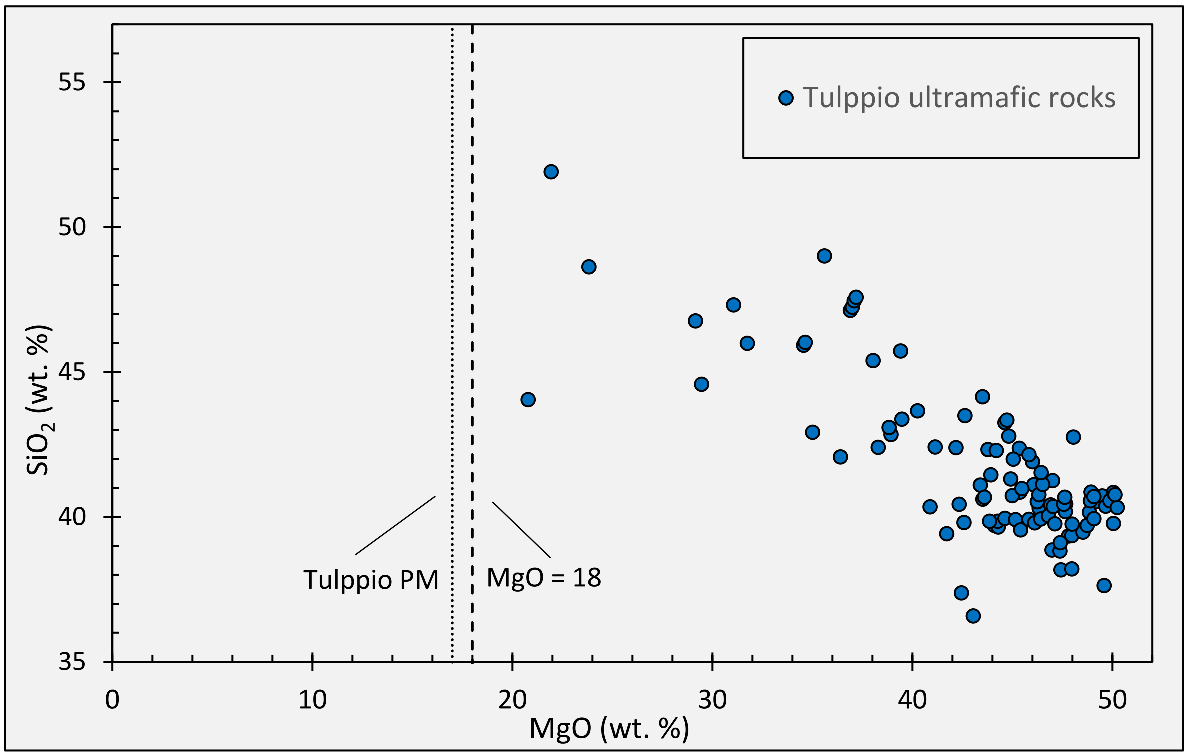

Figure 7.28: Compositions of the rocks of the Tulppio ultramafic complex shown in a MgO vs. SiO_2 plot. Dotted line is the estimation of the parental magma (PM) MgO content for the Tulppio ultramafic complex (see Section 8.3.1) and dashed line represents the MgO value for identification of komatiites (cf. Le Bas, 2000).

Aluminum in komatiitic rocks of Tulppio (0.1–7.7 wt.% Al_2O_3) shows distinct linear trend controlled by accumulation of olivine (Figure 7.29). On average, the Al_2O_3 is 1.7 wt. %. Titanium content in ultramafic rocks of Tulppio show similar olivine-controlled linear trend as aluminum (Figure 7.30). These trends reflect to a system that fractionates only olivine (±chromite), and later pyroxene, thus enriching the residual in Al and Ti. Analyses show values from under detection limit (0.003 wt.%) to 0.37 wt.% TiO_2 with an average at 0.07 wt. % TiO_2. Slight scatter is seen at lower MgO values.

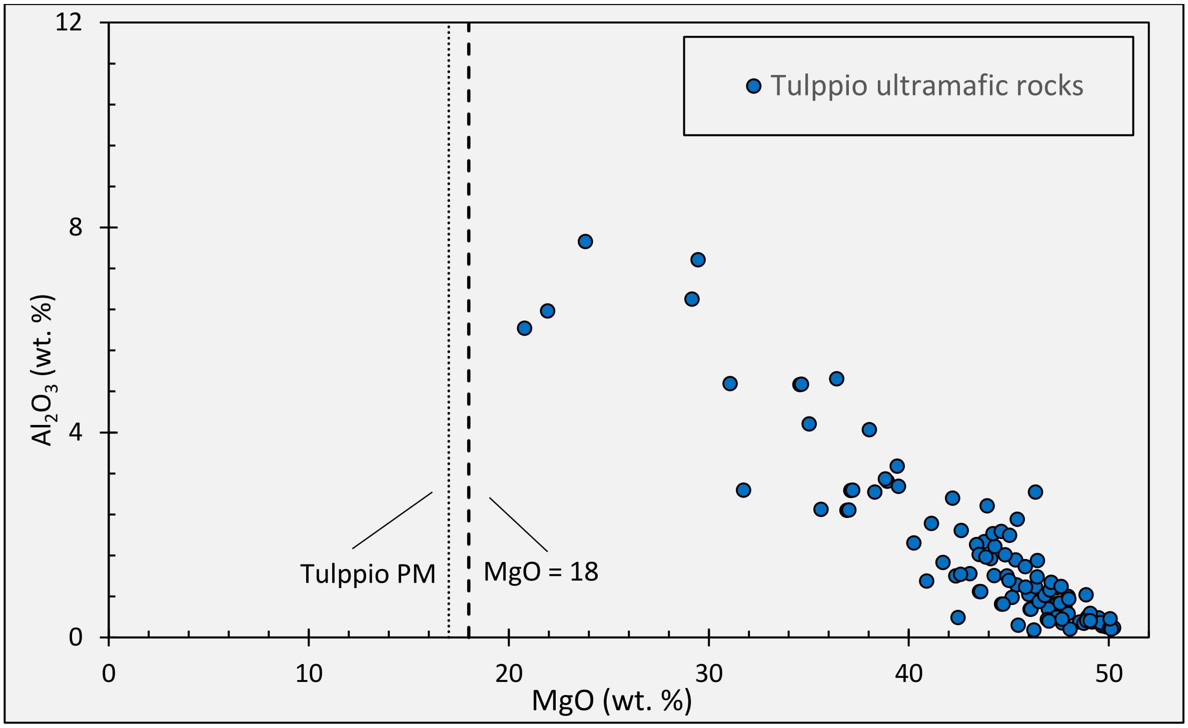

Figure 7.29: Compositions of the rocks of the Tulppio ultramafic complex shown in a MgO vs. Al_2O_3 plot. Dotted line is the estimation of the parental magma (PM) MgO content for the Tulppio ultramafic complex (see Section 8.3.1) and dashed line represents the MgO value for identification of komatiites (cf. Le Bas, 2000). The change in the Y-axis scaling from previous MgO vs. Al_2O_3 plot (Figure 7.22) should be noted.

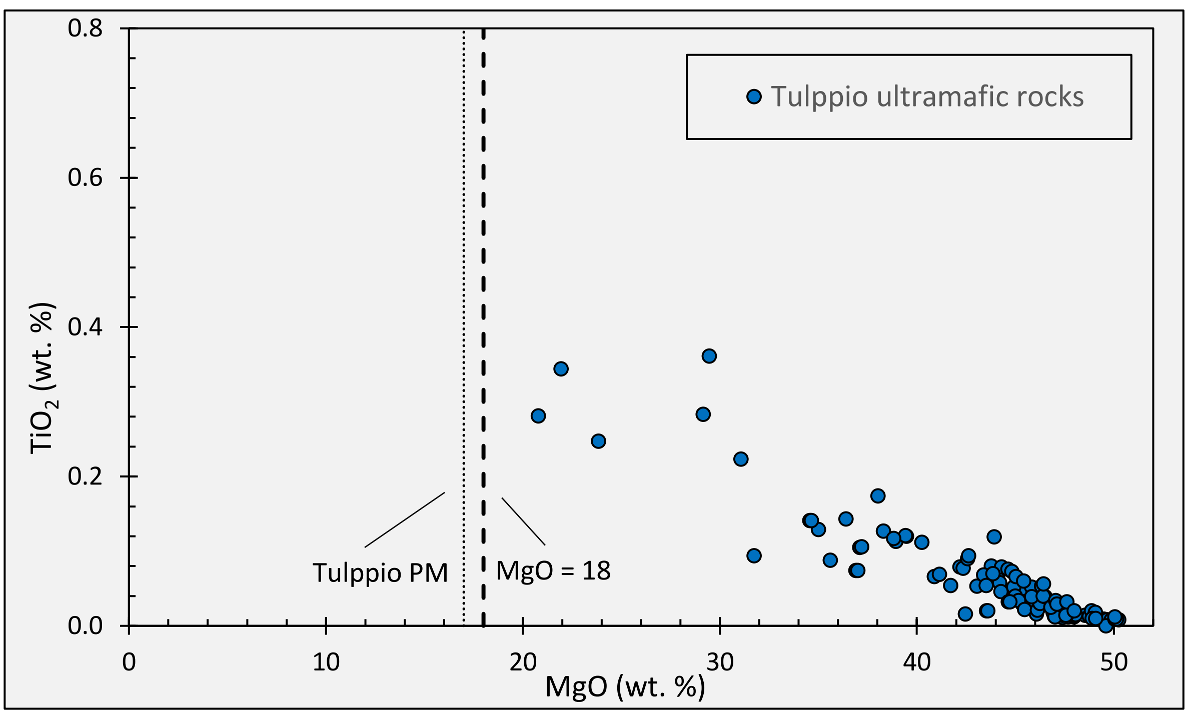

Figure 7.30: Compositions of the rocks of the Tulppio ultramafic complex shown in a MgO vs. TiO_2 plot. A negative correlation with slight scatter is distinct. Dotted line is the estimation of the parental magma (PM) MgO content for the Tulppio ultramafic complex (see Section 8.3.1) and dashed line represents the MgO value for identification of komatiites (cf. Le Bas, 2000). The change in the Y-axis scaling from previous MgO vs. TiO_2 plot (Figure 7.23) should be noted.

With the exception of two samples, all analyses from the Tulppio ultramafic complex plot into the AUK in the Al_2O_3/TiO_2 plot (Figure 7.31). Generally, these values are superchondritic (McDonough & Sun, 1995) and show enrichment in Al, as ratios higher than 40 values are common, with the highest being 69 and the average value being 28.

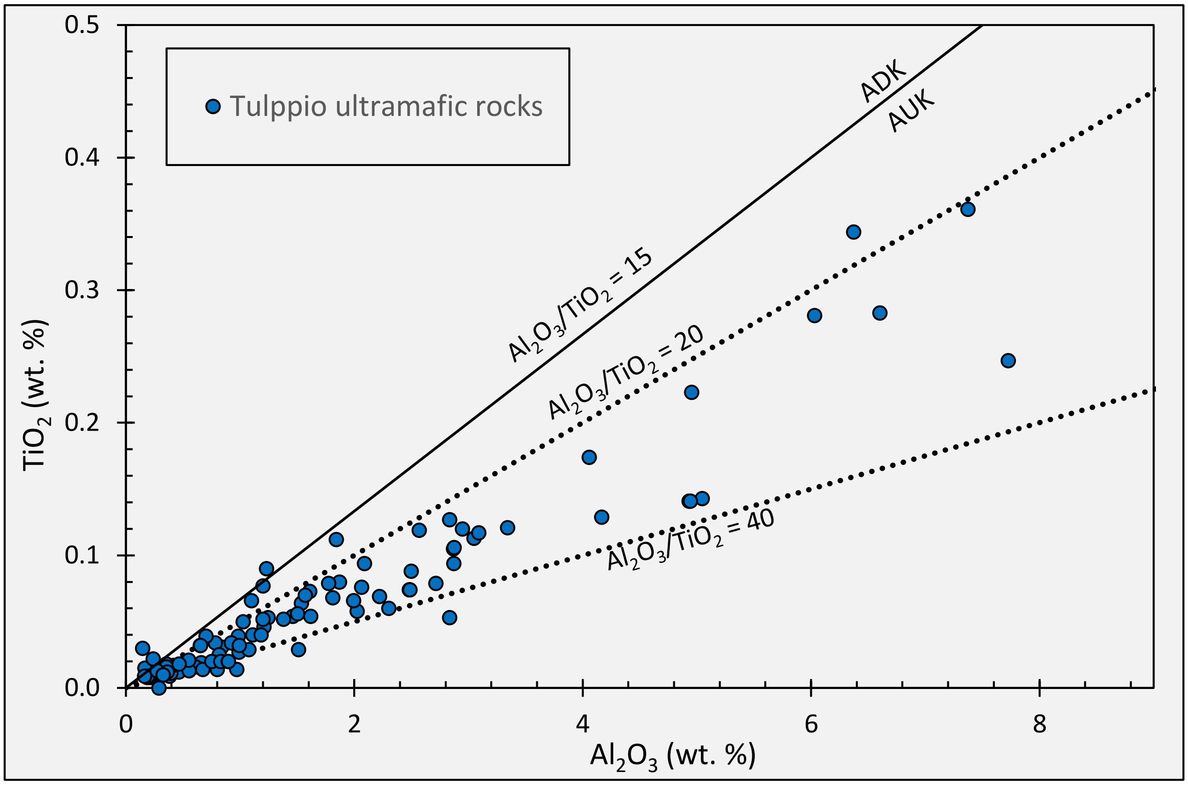

Figure 7.31: Ultramafic rocks of Tulppio on Al_2O_3 vs. TiO_2 plot. The solid line illustrates the classification of komatiitic rocks into ADKs (Al_2O_3/TiO_2 < 15) and AUKs (Al_2O_3/TiO_2 > 15) (cf. Section 2.3). The majority of samples show superchondritic ratios higher than 20. The highest values are observed in the samples with relatively low TiO_2 and Al_2O_3 contents both.

Nickel content of the Tulppio komatiites (Figure 7.32) ranges from 0.07 to 0.6 wt.%, with the highest values representing the Ni-PGE mineralization in the central parts of the dunitic body. Generally, Ni follows the olivine-control trend (Makkonen et al., 2017). However, a scattered population showing significant Ni-depletion is observed at 35–50 wt.% MgO.

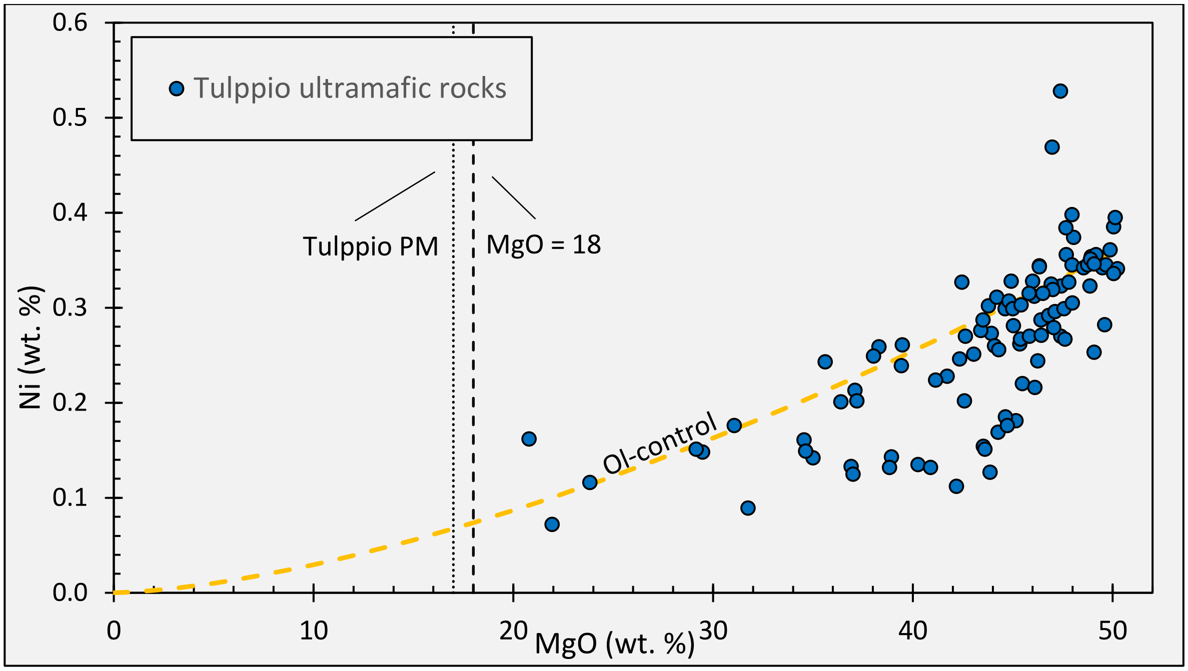

Figure 7.32: Compositions of the rocks of the Tulppio ultramafic complex shown in a MgO vs. Ni plot. Ni depletion line (yellow) by Makkonen et al., (2017). Dotted line is the estimation of the parental magma (PM) MgO content for the Tulppio ultramafic complex (see Section 8.3.1) and dashed line represents the MgO value for identification of komatiites (cf. Le Bas, 2000).

On the basis of Cr content, ultramafic rocks of the Tulppio dunitic show values of 0.1–1.4 wt.% Cr (Figure 7.33) with an average of 0.5 wt.% Cr. In a MgO vs. Cr plot samples from Tulppio show slight positive correlation to MgO at 20–35 wt. % MgO and heavy scatter at higher MgO values. A Cr-depleted population is distinct at 40–50 wt. % MgO.

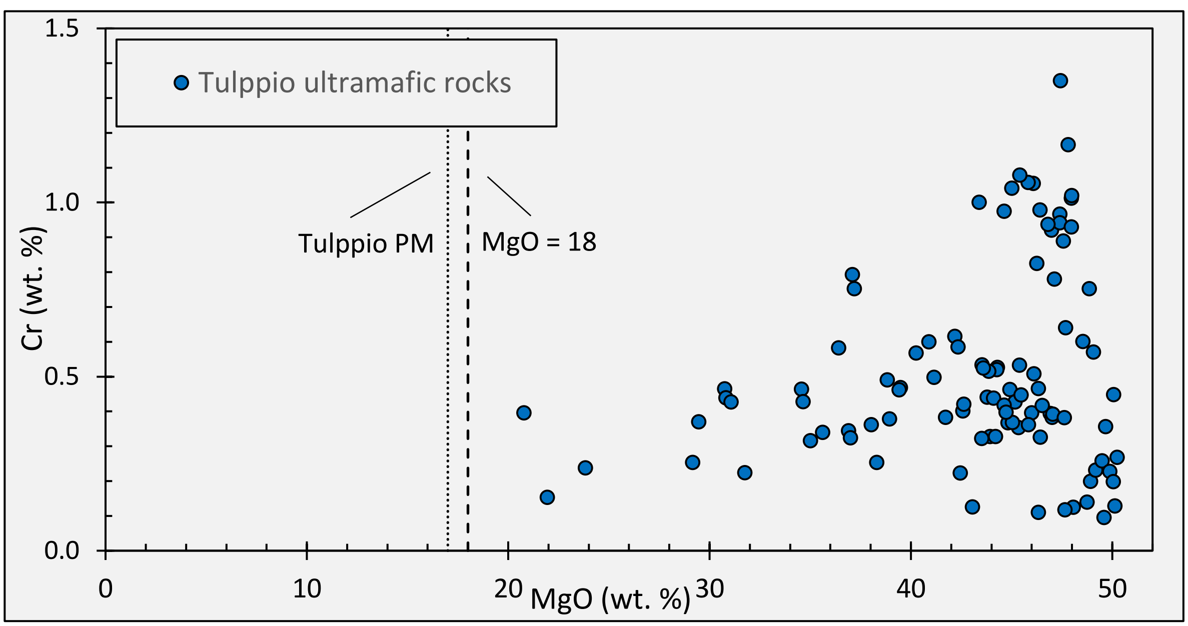

Figure 7.33: Compositions of the rocks of the Tulppio ultramafic complex shown in a MgO vs. Cr plot. Dotted line is the estimation of the parental magma (PM) MgO content for the Tulppio ultramafic complex (see Section 8.3.1) and dashed line represents the MgO value for identification of komatiites (cf. Le Bas, 2000).

Rare earth elements of the ultramafic complex of Tulppio show rather flat trends in a REE-diagram, with some variation in LREE (Figure 7.34). Some variation in Eu content, including both negative and positive anomalies, is observed. The majority of the REE analyses gave elemental concentrations below detection limits and consequently the REE content of Tulppio is likely to be more chondritic than the REE diagram suggests.

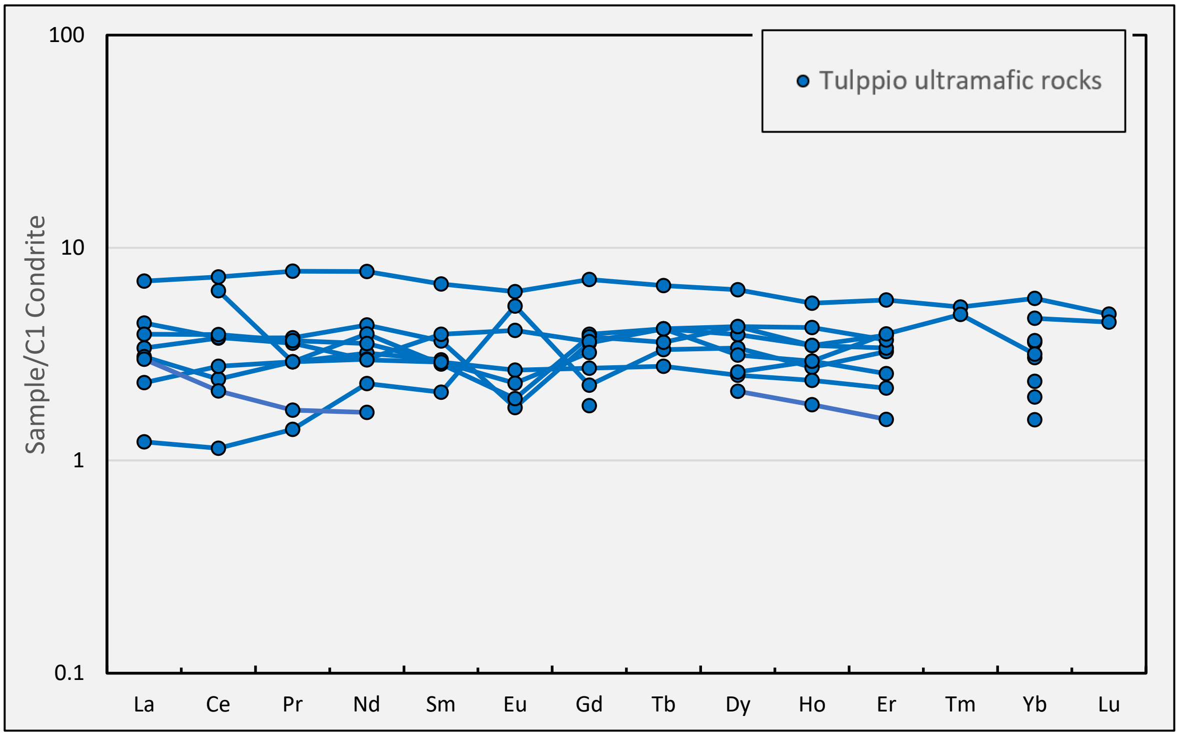

Figure 7.34: C1-chondrite normalized (McDonough & Sun, 1995) REE plot of the ultramafic rocks forming the Tulppio ultramafic complex. Not all REE analyses with low concentrations are included in the plot, as unbroken patterns were favored.

7.3.3 Värriöjoki ultramafic complex

On a MgO vs. SiO_2-plot, with the exception of two samples (komatiitic basalts), all of the komatiitic rocks of the Värriöjoki ultramafic complex have a MgO content higher than 25 wt.% with the main population at 40–50 wt.% MgO representing olivine meso- to adcumulates and their metamorphosed equivalents (Figure 7.35). Rocks from the Värriöjoki and Venehaara blocks show the widest spectrum of MgO contents (17.1–46.3 wt.%, respectively), whereas MgO content is 39–47 wt.% in the Liessijoki block and 25–42 wt.% in the Leppäselkä block. A notable feature is the absence of rocks at 30–33 wt.% MgO.

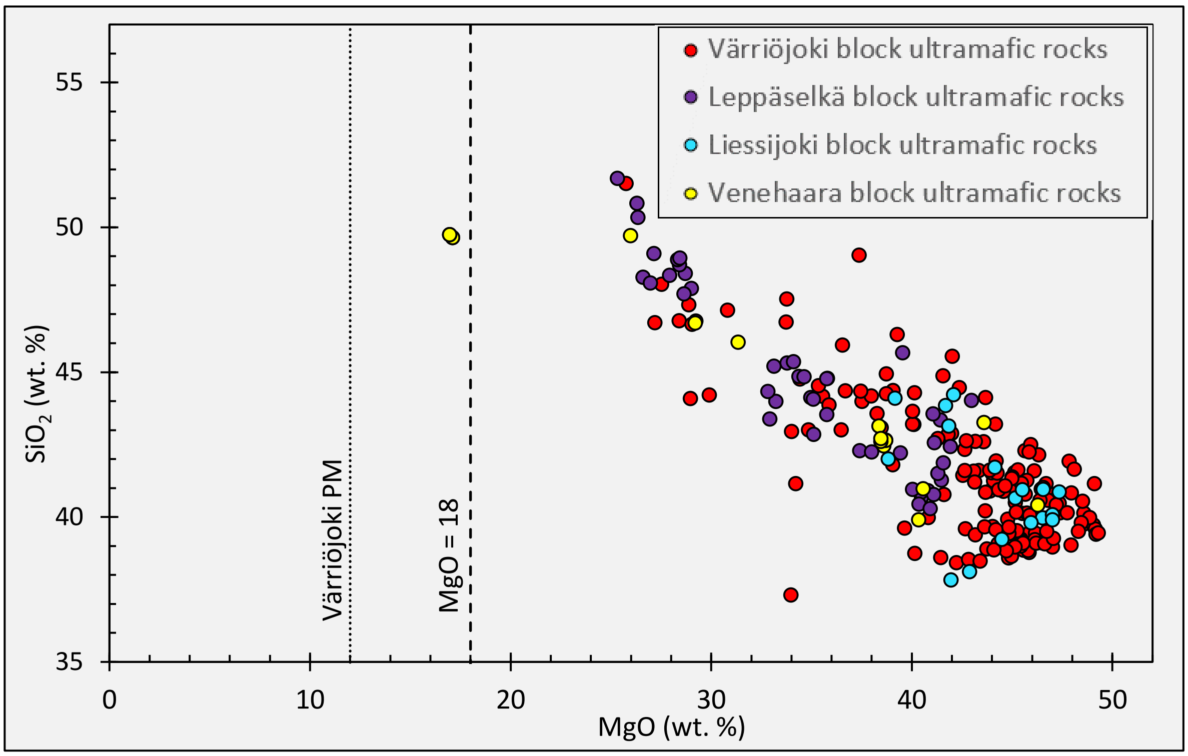

Figure 7.35: Compositions of the rocks of the four blocks forming the Värriöjoki ultramafic complex on MgO vs. SiO_2 plot. There appears to be a gap of compositions at 30–33 wt.% MgO. Dotted line is the estimation of the parental magma (PM) MgO content for the Värriöjoki ultramafic complex (see Section 8.3.2) and dashed line represents the MgO value for identification of komatiites (cf. Le Bas, 2000).

On MgO vs. Al_2O_3 plot, komatiitic rocks of Värriöjoki complex form a trend typical of olivine-controlled fractionation (Figure 7.36). Some samples from Värriöjoki and Leppäselkä blocks at 25–32 wt.% and 39–44 wt.% MgO show relatively depleted Al contents, however. On the basis of their MgO/Al_2O_3 trends, the rocks in four blocks forming the Värriöjoki ultramafic complex do not seem to differ notably.

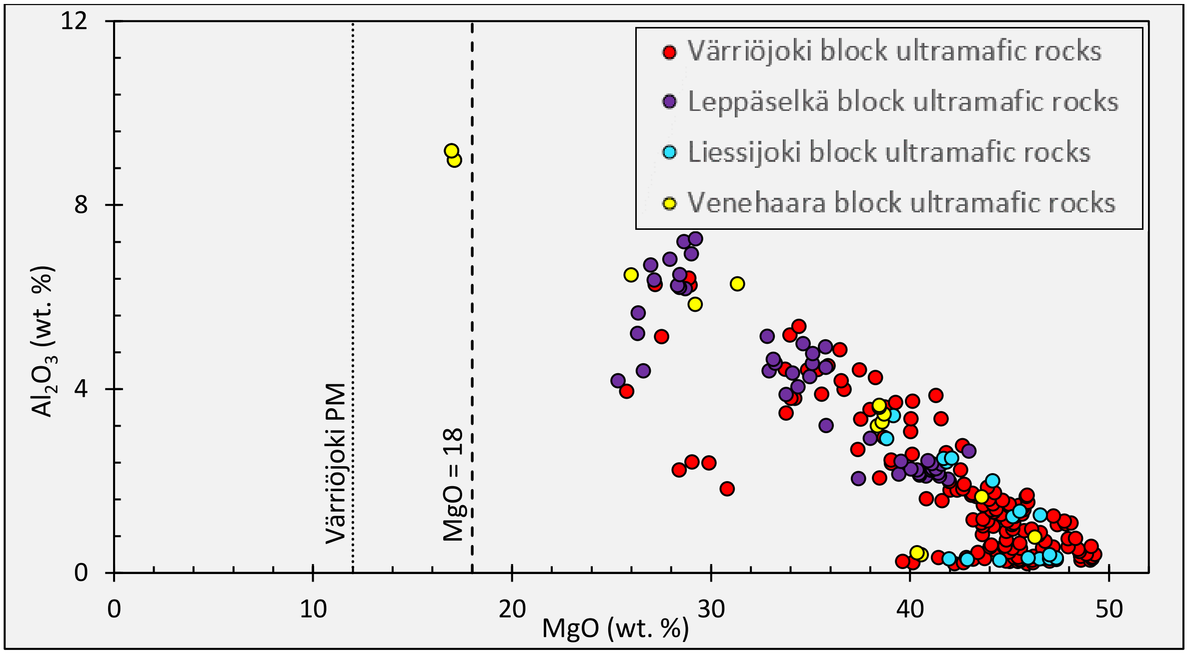

Figure 7.36: Compositions of the rocks of the four blocks forming the Värriöjoki ultramafic complex on MgO vs. Al_2O_3 plot. Different bodies are identified by colors. Dotted line is the estimation of the parental magma (PM) MgO content for the Värriöjoki ultramafic complex (see Section 8.3.2) and dashed line represents the MgO value for identification of komatiites (cf. Le Bas, 2000).

Titanium in the ultramafic rocks of Värriöjoki complex correlates with Al content, as these form similar plots against MgO (Figure 7.37). The same samples that show depleted Al_2O_3 contents also show depleted TiO_2 contents and plot outside of the main trend.

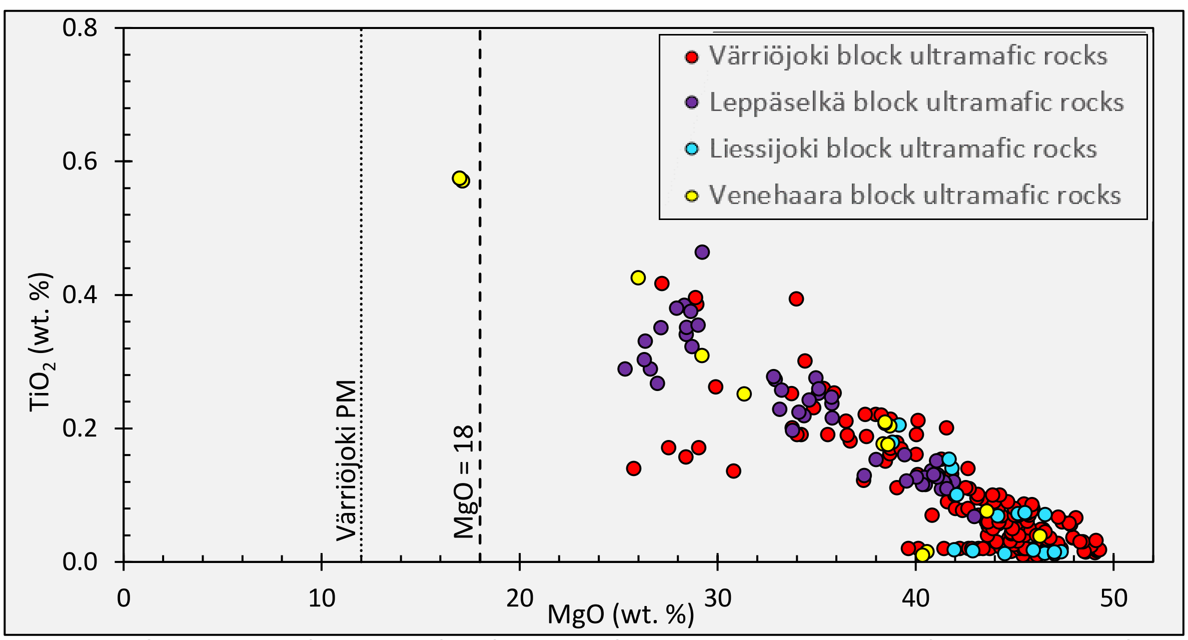

Figure 7.37: Compositions of the rocks of the four blocks forming the Värriöjoki ultramafic complex on MgO vs. TiO_2 plot. Different bodies are identified by colors. Dotted line is the estimation of the parental magma (PM) MgO content for the Värriöjoki ultramafic complex (see Section 8.3.2) and dashed line represents the MgO value for identification of komatiites (cf. Le Bas, 2000).

The komatiitic rocks of the Värriöjoki ultramafic complex are mostly AUK type and without clear differences between the four blocks in this respect (Figure 7.38). The majority of the analyzed samples plot into the field delimited by Al_2O_3/TiO_2 ratios of 15 and 20, whereas a small population shows ADK Al_2O_3/TiO_2 ratios at 1.5–2.0 wt.% Al_2O_3.

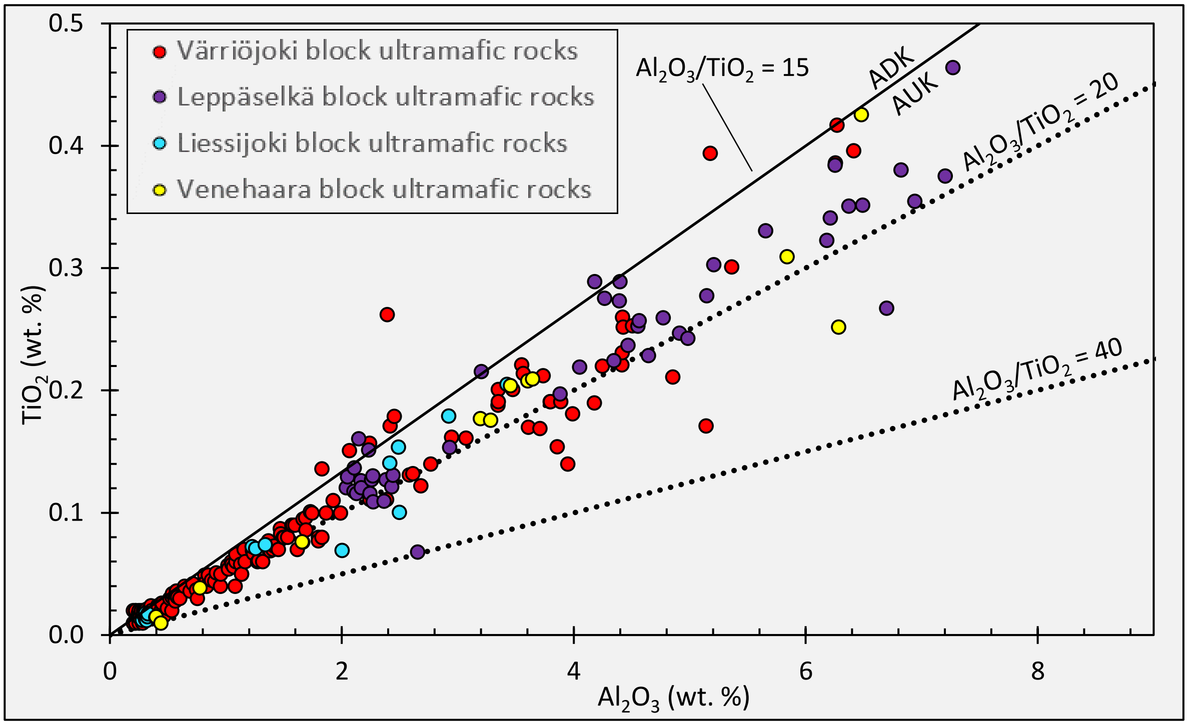

Figure 7.38: Ultramafic rocks of Värriöjoki on Al_2O_3 vs. TiO_2 plot. The solid line illustrates the classification of komatiitic rocks into ADKs ($Al_2O_3/TiO_2 < 15$) and AUKs ($Al_2O_3/TiO_2 > 15$) (cf. Section 2.3). Majority of rocks are AUKs, whereas several samples from the Värriöjoki and Leppäselkä blocks show ADK-type ratios.

Nickel content in the komatiites of the Värriöjoki ultramafic complex mainly conform to olivine-control trend (Makkonen et al., 2017) with the proportions ranging from 0.08 to 0.49 wt.% Ni (Figure 7.39). Slight depletion in Ni is seen at 27–31 wt.% MgO, whereas at > 30 wt.% MgO scattering increases for all the blocks except Venehaara. Slightly enriched and depleted values are observed especially at 40–50 wt.% MgO.

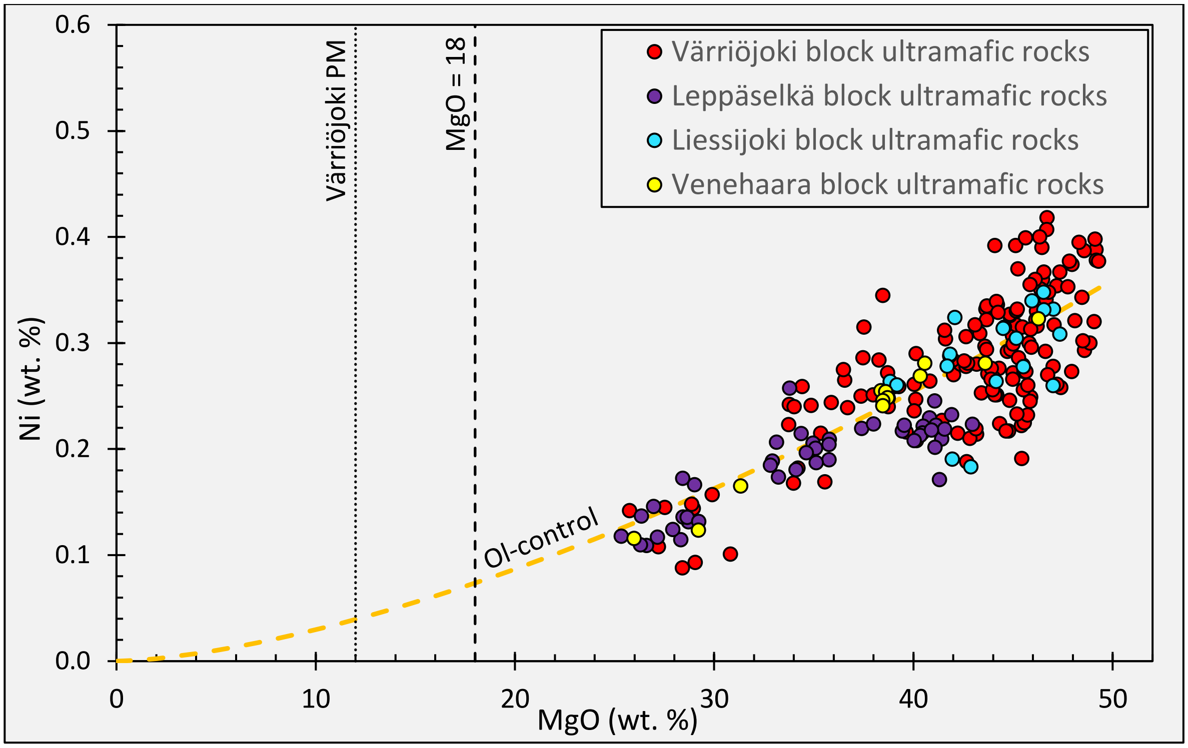

Figure 7.39: Compositions of the rocks of the four blocks forming the Värriöjoki ultramafic complex on MgO vs. Ni plot. Ni depletion line (yellow) by Makkonen et al., (2017). Dotted line is the estimation of the parental magma (PM) MgO content for the Värriöjoki ultramafic complex (see Section 8.3.1) and dashed line represents the MgO value for identification of komatiites (cf. Le Bas, 2000).

The komatiitic rocks of the Värriöjoki show chromium contents ranging from 0.08 to 3.4 wt.% Cr. In addition to linear trend at <35 wt. % MgO for all blocks, a distinct Cr-depleted population is seen at 35–50 wt.% MgO in the samples from Värriöjoki and Liessijoki blocks (Figure 7.40). Elevated Cr contents are also observed from the Värriöjoki block. Notable feature in the Leppäselkä and Venehaara blocks is the uniform and linear trend with no scatter in Cr.

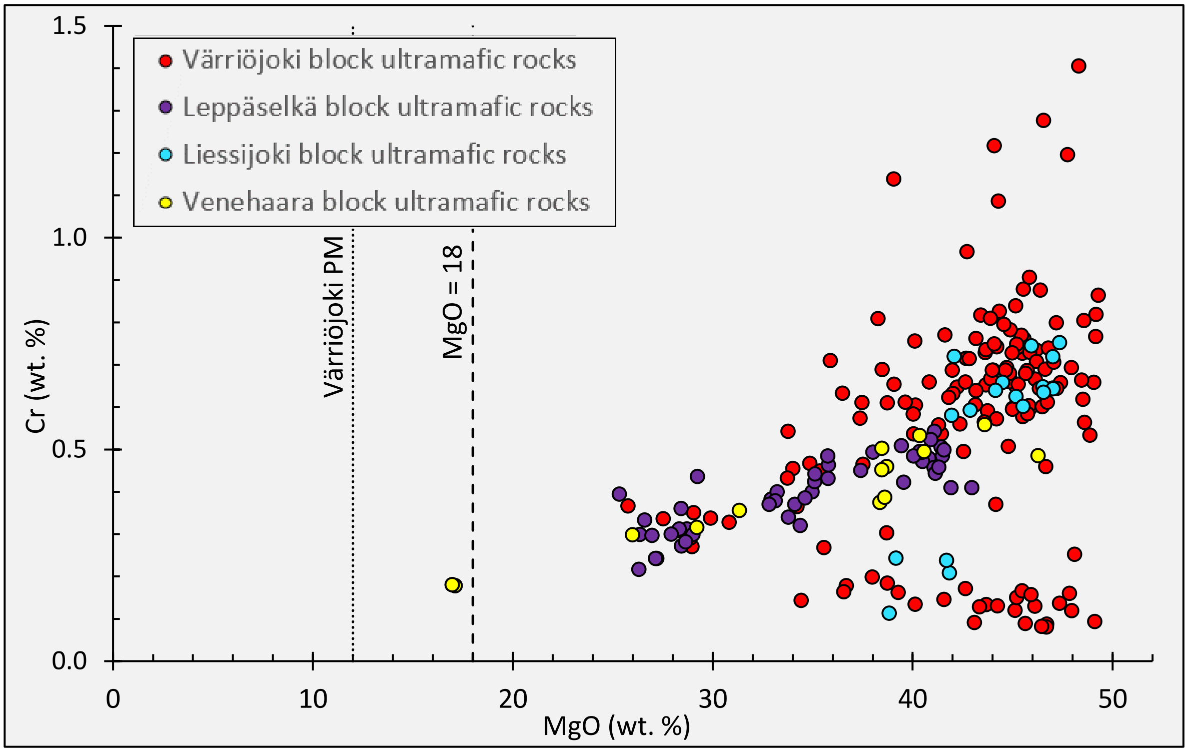

Figure 7.40: Compositions of the rocks of the four blocks forming the Värriöjoki ultramafic complex on MgO vs. Cr. Samples with Cr values exceeding 1.5 wt.% Cr are not included for illustrational reasons. In addition to a rather linear trend, heavily depleted Cr contents are detected from Värriöjoki and Liessijoki blocks.

The komatiitic rocks of Värriöjoki show slight enrichment in LREE and distinct negative Eu anomalies. In a REE diagram (Figure 3.41), significant differences in shapes of the trend lines are not observed with the exception of two samples from the Leppäselkä block with $(La/Sm)_N > 1$. These samples are from the bottom parts of a 550-m deep drill hole in the northern parts of the Leppäselkä block (Törmänen et al., 2007). Most of the samples from the Värriöjoki ultramafic complex show superchondritic REE concentrations.

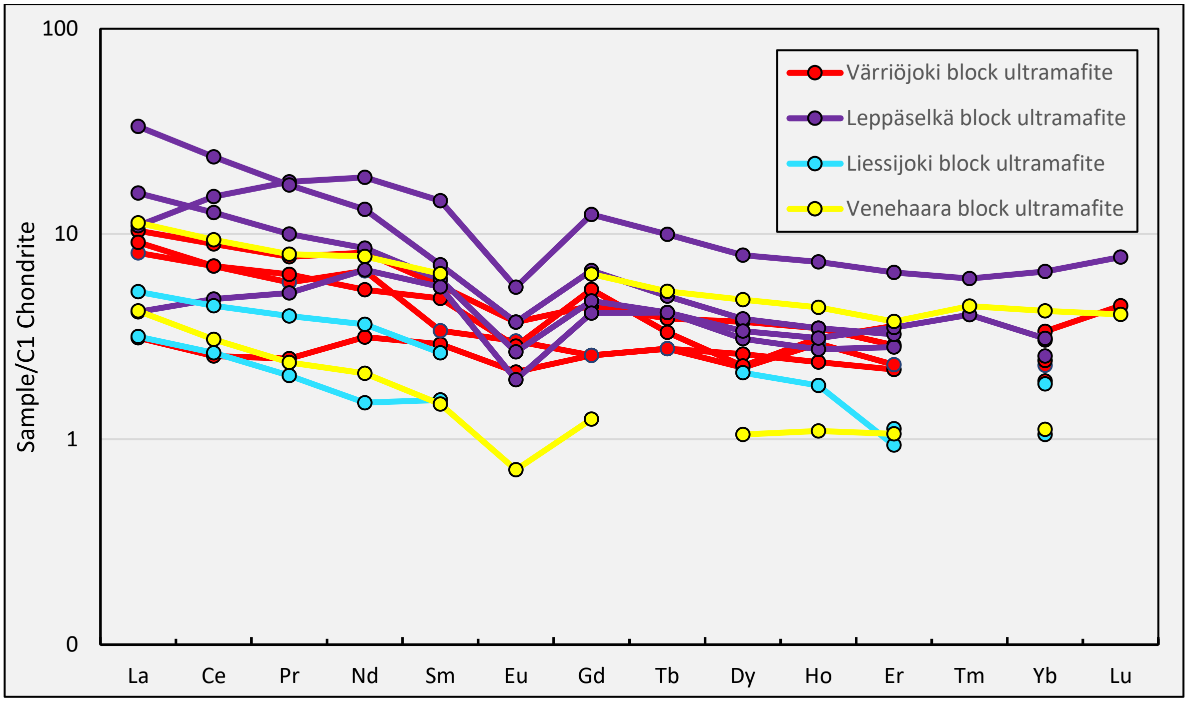

Figure 7.41: C1-chondrite normalized (McDonough & Sun, 1995) REE plot of the ultramafic rocks forming the Värriöjoki ultramafic complex. Slightly elevated LREE contents and negative Eu anomalies are definitive features. Due to the large amount of analyses, with many of them forming broken patterns, only the representative analyses are included in the illustration.

7.4 Mineral chemistry

Mineral chemical data from olivines that were considered magmatic were acquired from the samples described in Section 6.4 from Tulppio and Värriöjoki. Primary magmatic olivine was not found from the Jänesselkä mafic-ultramafic complex and thus no analyses from Jänesselkä are included in these results.

Olivine grains analyzed from Värriöjoki have 39.5 to 50.3 wt. % MgO and 8.1–15.4 wt. % FeO. These correspond to forsterite contents of Fo_{78}–Fo_{92} (Figure 3.42), with the lowest values measured from olivine in the metaperidotite of the main Värriöjoki block. Olivines from the Tulppio ultramafic complex are from two samples from the least altered core of the dunitic body. These samples contain the only magmatic olivine available from Tulppio. Probably, due to the low amount of samples, these show less compositional variation than in Värriöjoki, with 50–51 wt. % MgO and 7.8–8.5 wt. % FeO. Corresponding forsterite content is Fo_{92}. Ni content in olivine ranges from 0.45 to 0.55 wt. % in Tulppio and from 0.2 to 0.44 wt. % in Värriöjoki (Figure 3.42).

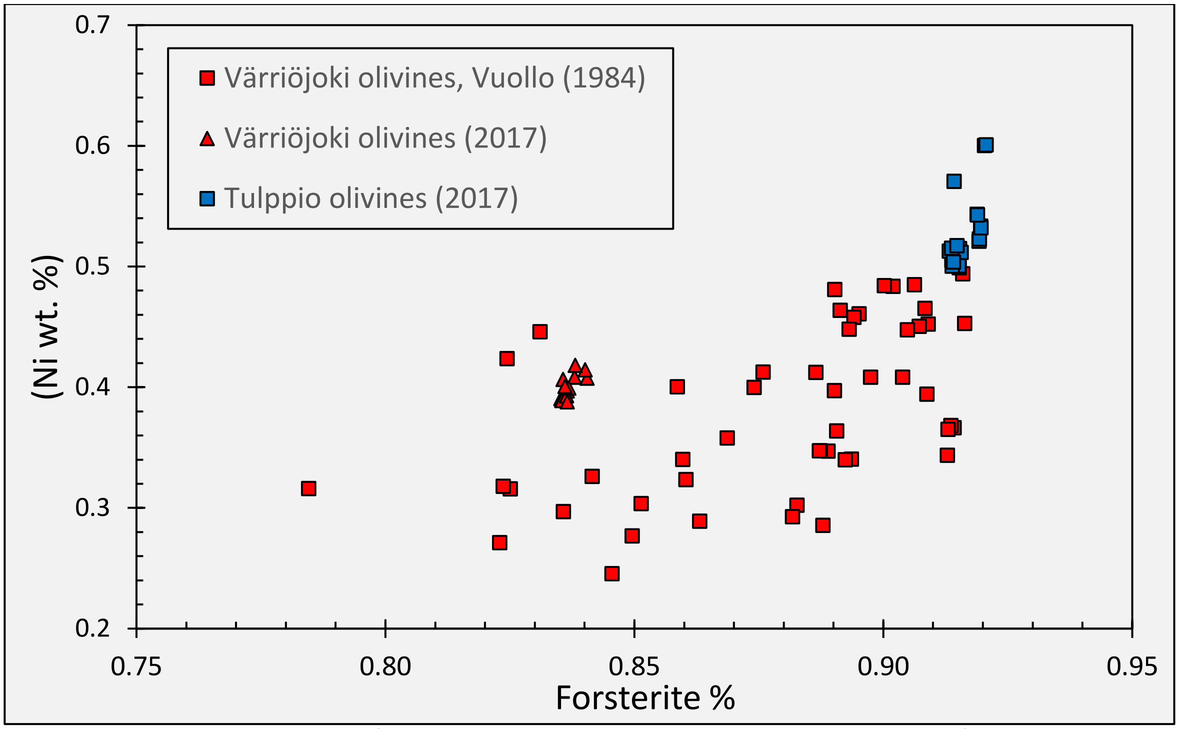

Figure 7.41: Forsterite vs. Ni plot of analyzed olivines in the Tulppio and Värriöjoki ultramafic complexes. Large scatter in 1984 samples from Värriöjoki is partly due to only one analysis being performed from each sample (i.e., each data point represents a different sample).

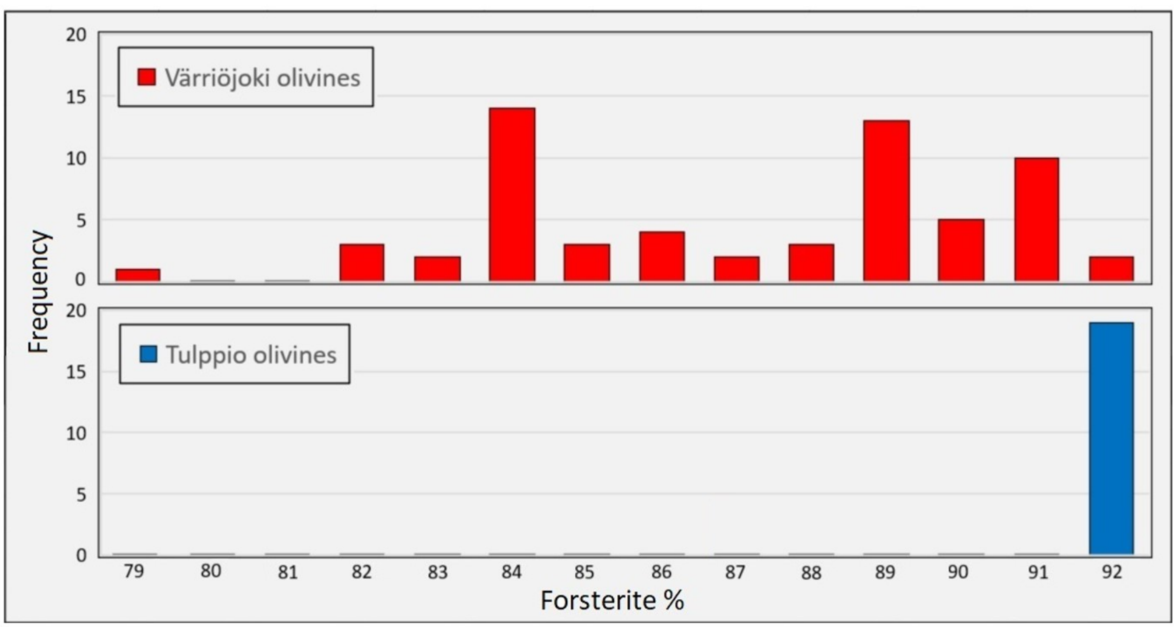

Figure 7.42: Histogram of Fo contents of olivines from the Tulppio and Värriöjoki ultramafic complexes.

8 DISCUSSION

This chapter is divided into two parts: the first considers the petrogenesis of the Jänesselkä mafic-ultramafic complex and the second considers petrogenesis and comparison of the ultramafic complexes of Tulppio and Värriöjoki. This division is based on field observations, petrographical studies and geochemical examinations, as the ultramafic rocks of Jänesselkä show different features compared to the other two complexes.

8.1 Origin of the Jänesselkä mafic-ultramafic complex

The gabbroic rocks found in the central part of the Jänesselkä mafic-ultramafic seem to belong to the same formation as the surrounding ultramafic rocks. For example, in terms of their Al_2O_3 and TiO_2 contents, the gabbroic rocks fit as continuations of the main differentiation trends of the ultramafic rocks (Figures 7.22 and 7.23). Another geochemical evidence is the Ni and Cr contents in the gabbroic rocks of Jänesselkä (mean values of 600 ppm Ni and 400 ppm Cr) (Figures 7.25 and 7.26) that correspond to suites with assumed komatiitic origin (Figures 8.3 and 8.4). These are notably higher than, e.g., mean values in ocean ridge basalts globally (92 ppm Ni, 249 ppm Cr) (Gale et al., 2013) or gabbroic rocks in Proterozoic ophiolites in northeastern Finland (98 ppm Ni, 132 ppm Cr) (Kontinen, 1987). This could be a consequence of high concentrations of these metals in the parental magma (cf. komatiitic magma) that formed both the gabbroic and ultramafic rocks in Jänesselkä. In terms of field observations, the gradual rock type change from altered olivine cumulates through altered pyroxenites to mafic rocks and uniform deformation histories of these rocks also suggest a common origin for the gabbroic and ultramafic rocks in Jänesselkä.

When considering the classic model of komatiitic flow field (Hill, 2001), flow type including gabbroic rock compositions is not included in it, with the exception of gabbroic cumulates formed from residual melts in some thick meso- to adcumulate bodies (Perring et al., 1995). As olivine-bearing meso- or adcumulates or their metamorphosed equivalents have not been traced from the Jänesselkä mafic-ultramafic complex, it is likely that the gabbroic rocks in Jänesselkä represent rocks formed through fractional crystallization in a relatively slowly cooled system. This is supported by the variety of rock types observed in the central parts of the complex: for example, the anorthosite xenolith in the leucogabbro could represent a roof pedant from the upper parts of the magma chamber. If Jänesselkä does not belong to any flow facies of komatiitic sequence, it possibly differs in origin from the majority of the komatiitic rocks that form the Tulppio metavolcanic belt and have been interpreted as komatiitic lavas (Juopperi, 1994; Papunen, 2003).

In order to decipher the petrogenesis of the Jänesselkä mafic-ultramafic complex, a parental magma calculation was performed. Because magmatic olivine is not present in the rocks, calculation was performed indirectly by estimating the representative cumulus olivine forsterite content based on whole-rock compositional trends. Modeling is based on a Pearce diagram, where MgO and FeO are nominators and Al_2O_3 or TiO_2 are denominators (Makkonen et al., 2017). Because cumulative error, estimated as R^2, showed lower value ($R^2 = 0.732$) in the case of TiO_2 denominator than for Al_2O_3 denominator ($R^2 = 0.592$), the former was used in the calculation. Based on this, the forsterite content of the accumulated olivine in Jänesselkä is Fo_{81}. From the composition of olivine (Figure 8.1) a parental magma calculation using whole-rock geochemistry was attempted. However, because of scatter ($R^2 < 0.3$ in the MgO vs. FeO) a reasonable estimation for MgO/FeO value was not achieved. Instead, liquid MgO content was calculated based on Mg-number and empirical equation derived from various komatiitic suites globally: Mg-number = $0.1739 \times \ln$ MgO (wt.%) + 0.2391 (Makkonen et al., 2017). Data for the equation includes 321 analyses and originates from the studies by Fiorentini et al., (2010) and Barnes & Fiorentini (2012). It should be noted that the equation has been calculated from the compositions of Archean komatiites, whereas consensus about the absolute age of the target complexes of this study is lacking. Outcome of this calculation was a parental magma with 6.6 wt.% MgO.

A parental magma with ~7 wt.% MgO is basaltic and corresponds to the volumetrically minor gabbroic rocks forming the Jänesselkä mafic-ultramafic complex. This means that the formation of the large volume of high-MgO rocks required efficient accumulation of olivine from relatively large volumes of such basaltic magma, that based on the high Ni and Cr contents, may have been a residual of a fractionated komatiitic primary melt. The possibility of Jänesselkä mafic-ultramafic complex representing an independently fractionated mafic intrusion should thus be considered as a viable option. In this model, the majority of the mafic to intermediate rocks that were involved have either been eroded away or do not outcrop. In terms of geochemistry, notably uniform Ni and Cr contents in Jänesselkä reflect accumulation of these elements with olivine (and minor chromite).

In Finland, basaltic to high-Mg basaltic systems that have formed komatiitic cumulate compositions are recognized from multiple locations. For example, some Archean complexes i.e., those in the Suomussalmi greenstone belt were formed from ~10–15 wt.% MgO komatiitic basalts, whereas corresponding Proterozoic ultramafic-mafic cumulates have formed from even more evolved basaltic magmas (Makkonen et al., 2017). Notably, preliminary U-Pb age determination results from the gabbro of Jänesselkä suggest an age of 2.4–2.5 Ga (Tepsell, 2018). In northern Fennoscandian shield, mafic-ultramafic rocks of this age form a group of PGE-bearing layered mafic intrusions. The 2.44 Ga Akanvaara mafic layered intrusion, close to Jänesselkä, is interpreted to have formed from a low-Ti parental basaltic magma (Mutanen, 1997). This parental composition is similar to that of Jänesselkä. Ultramafic rocks are abundant at the assumed basin of the Akanvaara intrusion which may correspond to dominant rock types in Jänesselkä.

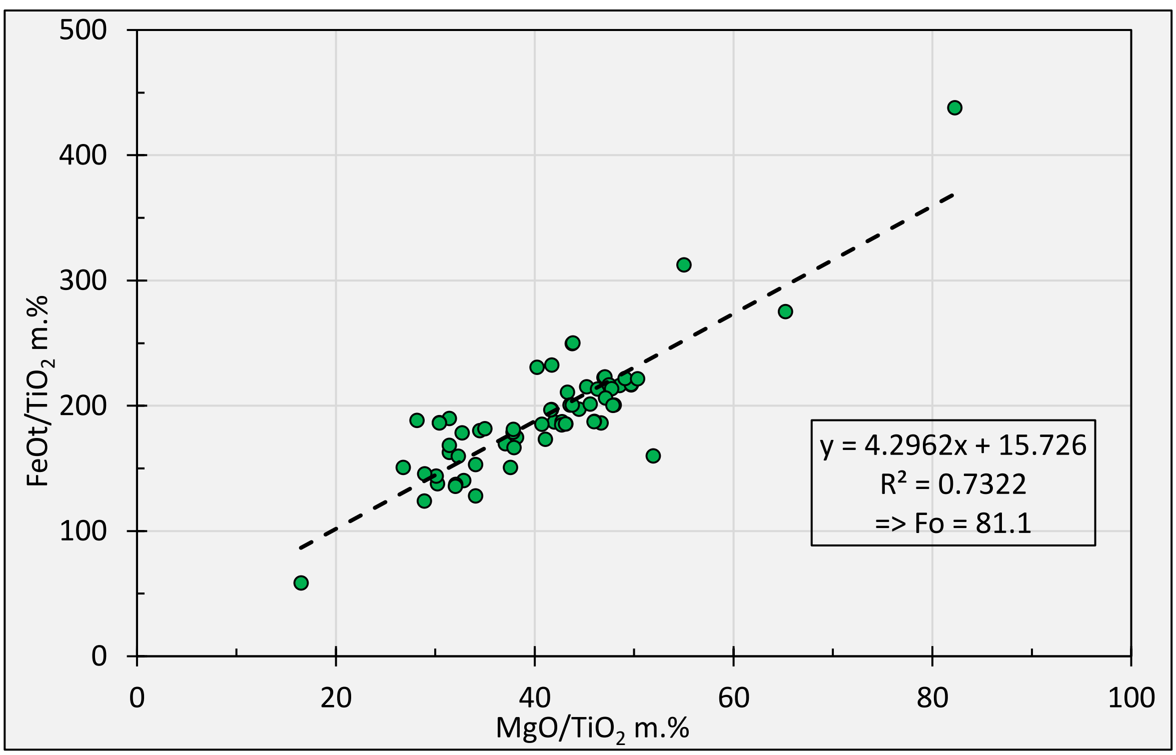

Figure 8.1: Pearce molecular MgO/TiO_2 vs. $FeOt/TiO_2$ plot of the Jänesselkä mafic-ultramafic complex. Forsterite content of the cumulus fraction is calculated using the method by Makkonen et al. (2017).

Two ultramafic bodies, with Sm-Nd ages of 2.45 Ga (Juopperi & Vaasjoki, 2001) are known from the Tuntsa metasedimentary belt, the lithotectonic unit 20 km south from Jänesselkä. Bodies of Peuratunturi and Koulumaoiva, interpreted as intrusions, are located within a 30-km radius from Jänesselkä and they consist mostly of olivine cumulates and their gabbroic differentiates (Iljina, 2003). Estimates of parental magma compositions are not available for them. Similarities in general geology with Jänesselkä are obvious, however, and the Peuratunturi and Koulumaoiva intrusions may represent unaltered counterparts of the Jänesselkä mafic-ultramafic complex. Another interesting but rather unstudied mafic intrusion in the proximity of the Jänesselkä mafic-ultramafic complex, is the Jäkäläharjut gabbroic body (Iljina, 2003) within in the Ahmatunturi granitoid complex.

Elevated LREE contents in komatiitic rocks are often considered a consequence of crustal contamination – a crucial process for formation of Ni-Cu-(PGE) mineralizations in mafic-ultramafic systems. The REE content of the Jänesselkä mafic-ultramafic complex was examined from this perspective. As MgO and CaO did not show correlation with changes in La/Sm, the effects of olivine accumulation and metamorphism were excluded as controlling factors. Nd is an incompatible element in high-MgO magmas and considerably enriched in continental crust (~11 ppm, Taylor & McLennan, 1995) relative to mantle (~1.2 ppm, Hoffman, 1988), and thus it was used as a relative measure of magma differentiation. When Nd is plotted against La/Sm, distinct correlation is seen (Figure 8.2) in the komatiitic compositions. It is therefore likely that variation in LREE contents in Jänesselkä cumulate pile are controlled by differentiation and, namely the amount of crustal component added to the magma. Together with in-situ contamination trough heating, pre-emplacement assimilation provides a plausible mechanism for input of crustal component to the magma.

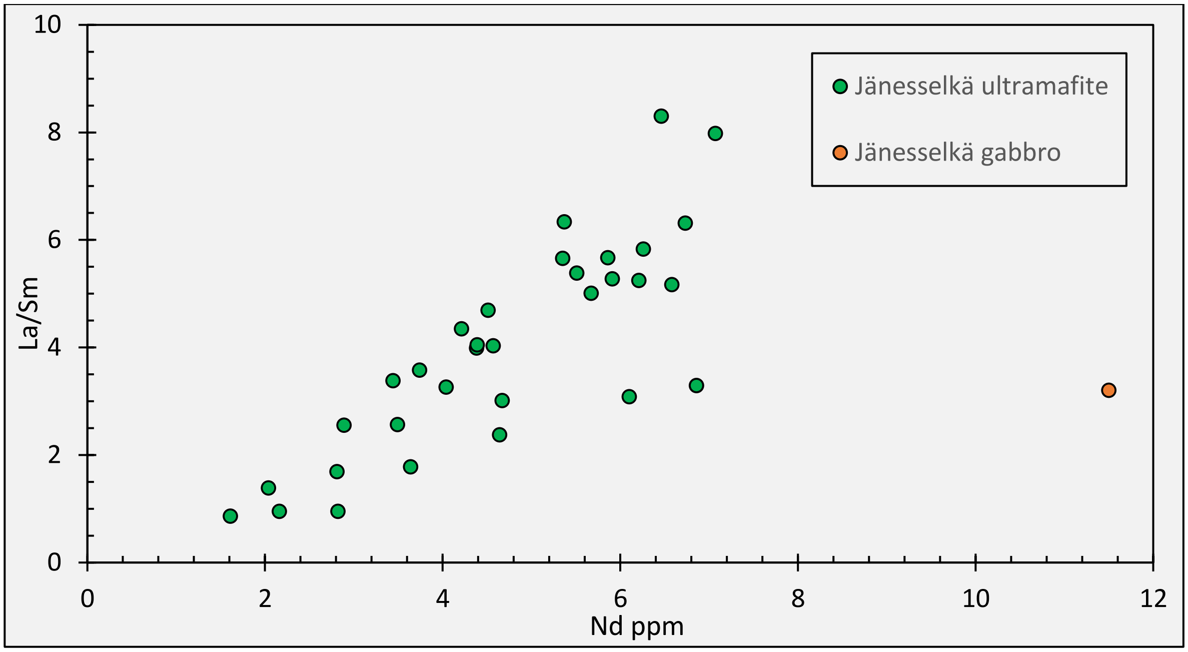

Figure 8.2: Rocks of the Jänesselkä mafic-ultramafic complex shown on a Nd vs. La/Sm. Plot is used to illustrate the overall addition of incompatible elements and simultaneous increase in LREE/MREE. The on off-trend sample is the gabbroic rock in the central parts of the complex. The difference in LREE/MREE related to komatiitic rocks in Jänesselkä could be explained with these rocks being formed through different physical mechanisms.

8.2 Characteristics of the ultramafic complexes of Tulppio and Värriöjoki

The major element geochemistry of all four komatiitic blocks forming the Värriöjoki ultramafic complex (Figures 7.35–7.40) is characterized by olivine control and only slight geochemical differences between these bodies can be observed. These include more uniform Ni and Cr contents in Leppäselkä and Venehaara (Figures 7.39 and 7.40) and overall lower MgO contents in Leppäselkä (Figure 7.35). The latter is most probably due to rather poor coverage of the sampling, as with the exception of three samples, all data available from the Leppäselkä block is from a single drill core (Törmänen et al., 2007). Therefore, the representativeness of these samples can be considered deficient. When the REE content of all four blocks is considered (Figure 7.41), no significant differences in the prevailing trends on REE plot can be seen and thus it is likely that these blocks are petrogenetically related to each other. This is supported by the geophysical interpretations about these blocks being connected. Based on these reasons, the ultramafic bodies of Värriöjoki, Liessijoki, Leppäselkä and Venehaara are treated as an entity.

The dominance of olivine cumulates controls the MgO content of both Tulppio and Värriöjoki, and significant difference cannot be observed between them in terms of MgO or

SiO_2. The larger amount of samples with MgO contents of below 30 wt.% observed in Värriöjoki can be a consequence of more comprehensive sampling. In addition, an important difference between Tulppio and Värriöjoki is that pyroxenitic and amphibolitic rocks are more abundant in the former. According to drilling, mafic volcanic rocks around the dunitic body are rather abundant in Tulppio, however (Heikura et al., 2010).

The ultramafic complexes of Tulppio and Värriöjoki differ slightly in both Ni (Figure 8.3) and Cr (Figure 8.4) contents. Notable variations in Cr at given MgO contents The Tulppio ultramafic rocks are generally more depleted in Ni and Cr and show less variation in Cr contents in relation to the samples from Värriöjoki. As other Ni-bearing minerals than olivine were not observed, it can be assumed that olivine was and still in some parts is the main host for Ni. Both complexes show significant scatter at high MgO contents. This most probably reflects to a system that migrates in and out from chromite saturated assemblage as olivine crystallization changes the SiO_2 content of the magma. This is typical for komatiitic systems (Barnes, 2006). The Cr-depleted population observed from both complexes is considered as prospective feature in komatiitic systems (Barnes, 1998). Such samples are more common from Värriöjoki in relation to Tulppio. In cumulus rocks chromium content is usually controlled by the amount of spinel as a cumulus mineral and thus precipitation and accumulation of chromite has been more efficient in the formation of the Värriöjoki dunites. Stability of chromite is usually controlled by changes in oxygen fugacity or/and in magma composition (Barnes, 1998).

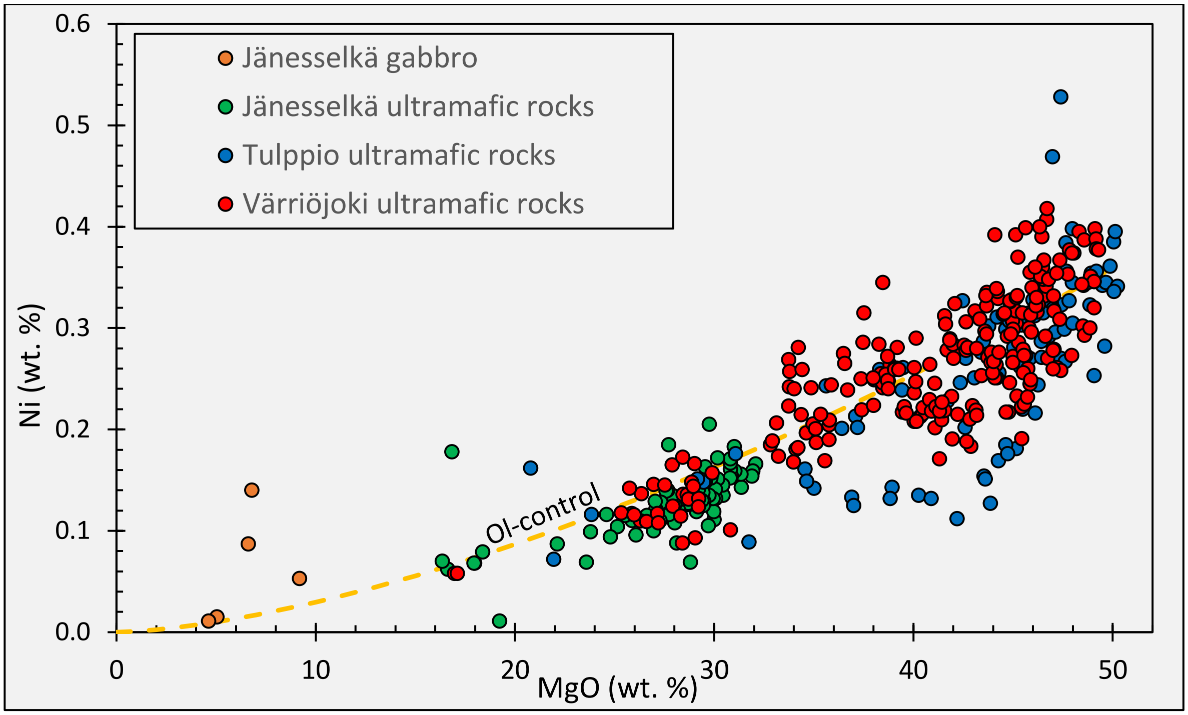

Figure 8.3: Compositions of the rocks of the Jänesselkä, Tulppio, and Värriöjoki ultramafic complexes shown in a MgO vs. Ni plot. Ni depletion line (yellow) by Makkonen et al., (2017).

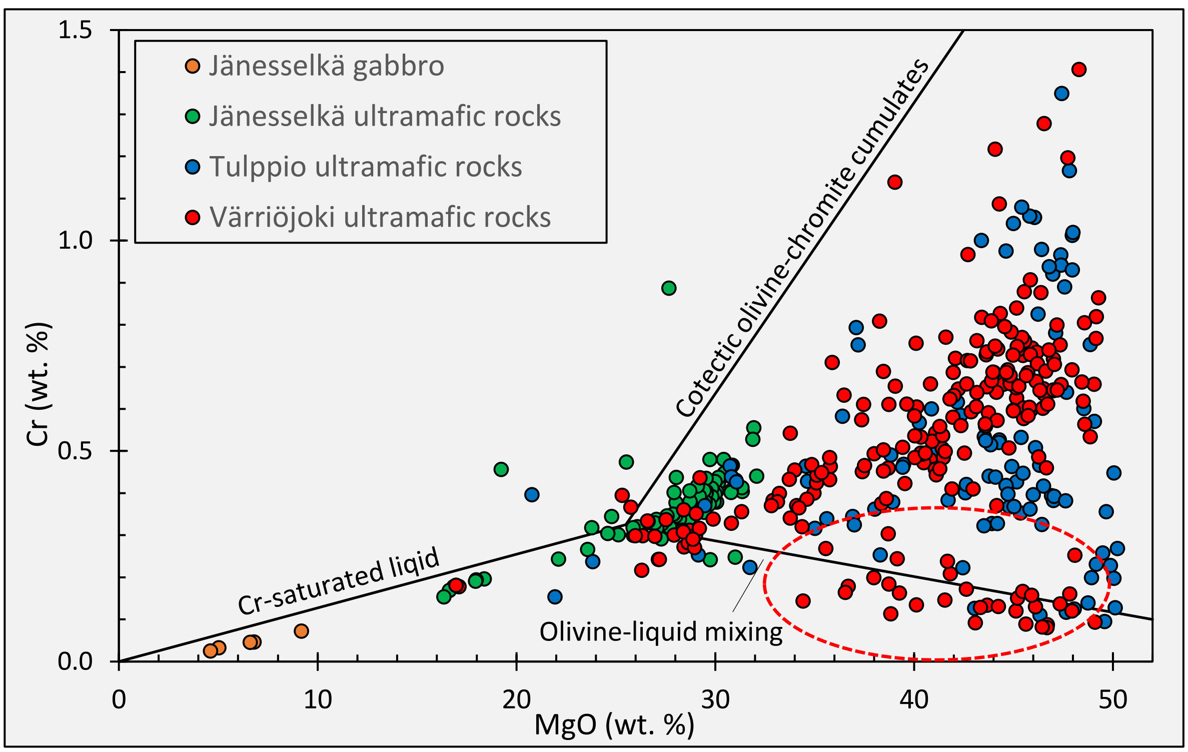

Figure 8.4: Compositions of the rocks of the Jänesselkä, Tulppio, and Värriöjoki ultramafic complexes shown in a MgO vs. Cr plot. Samples with Cr values exceeding 1.5 wt.% Cr are not included for illustrational reasons. Solid lines illustrate the trends for fractionation of chromite-saturated komatiitic liquids, olivine fractionation from chromite-undersaturated liquids and, cotectic olivine-chromite accumulation from chromite-saturated komatiitic liquids after Barnes (1998). The red ellipse indicates prospective samples in komatiitic systems after Barnes (2006).

The most significant major element geochemical differences between the ultramafic complexes of Tulppio and Värriöjoki are observed in terms of TiO_2 content. Enrichment in TiO_2 is distinctive in Värriöjoki in relation to Tulppio. In addition, Värriöjoki ultramafic rocks show more elevated TiO_2 relative to Al_2O_3. This is clearly illustrated in the Al_2O_3 vs. TiO_2 plot used for the classification of komatiites (Figure 8.5), where the majority of Värriöjoki rocks plot along the Al_2O_3/TiO_2 line representing the division to AUK and ADK types. The ultramafic rocks of Tulppio are almost uniformly AUK type.

The REE patterns of the Värriöjoki complex are notably different from the rather flat REE patterns of the Tulppio ultramafic complex. Whereas enrichment in LREE is not be observed in Tulppio, where average values of La/Yb are ~2.0, the elevated LREE abundances dominate in Värriöjoki with average La/Yb being ~4.8. These features suggest a rather primitive and uncontaminated magma for Tulppio, whereas a crustal component was probably involved in the formation of the Värriöjoki dunites.

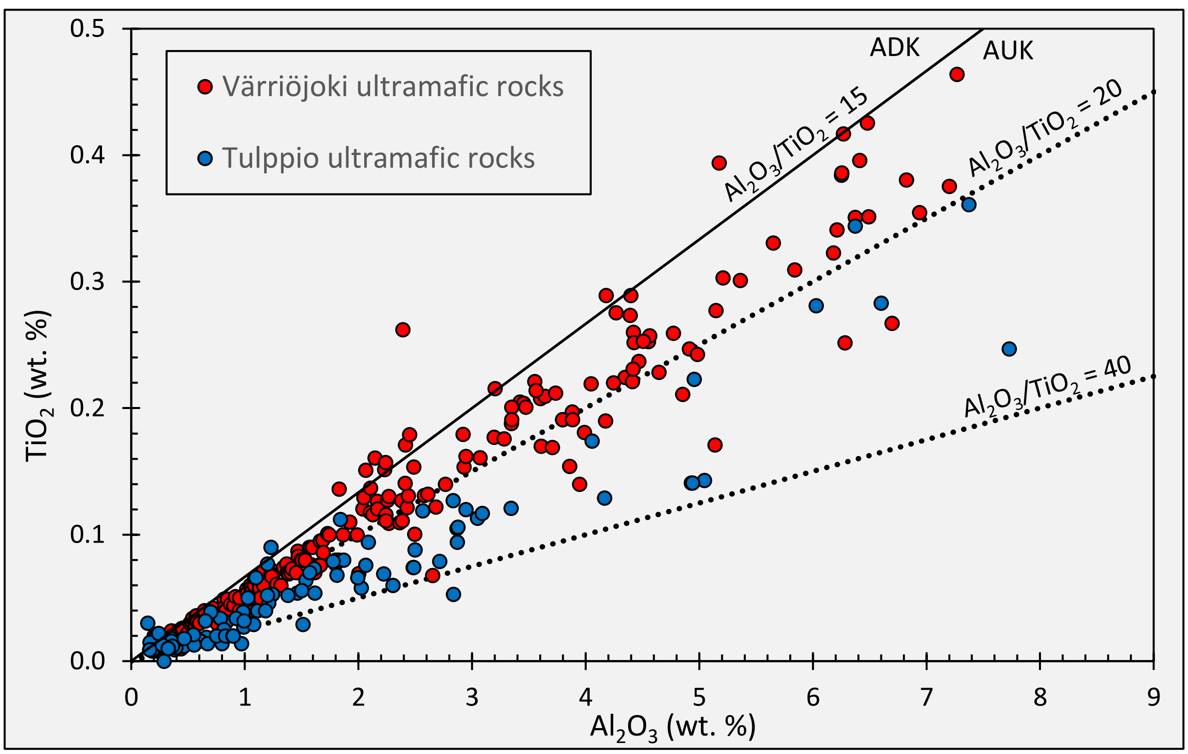

Figure 8.5: Ultramafic rocks of Tulppio and Värriöjoki shown on a Al_2O_3 vs. TiO_2 plot. Plot illustrates the classification of komatiites to ADK- ($Al_2O_3/TiO_2 < 15$) and AUK-type ($Al_2O_3/TiO_2 > 15$). The degree of Al depletion or Ti enrichment in Värriöjoki is higher compared to the ultramafic rocks of Tulppio.

The most distinct difference observed in the field is the rather unaltered and undeformed nature of the Värriöjoki ultramafic rocks, in contrast to Tulppio. In terms of deformation of the Siurujoki ultramafic complex, NW of the Värriöjoki main block, provides a good control point. Whereas the Värriöjoki complex is located in the TSB at the contact with the AGC, the Siurujoki complex is located inside the AGC, at a distance of one kilometer from the aforementioned contact of the lithotectonic units. Noteworthy features in the Siurujoki ultramafic rocks are heavy deformation and comprehensive alteration (Figure 8.6). These have not been observed in any significant extent from Värriöjoki. However, the nature of the contact between the lithotectonic units is vaguely known, and thus the initial position of these ultramafic complexes in relation to each other is unclear. Also, the substantial volume of the Värriöjoki dunitic body may have shielded the interior parts of it from alteration.

The aforementioned differences in the geochemistry between the ultramafic complexes of Tulppio and Värriöjoki can be explained by them being derived from different primary magmas possibly at different times, with Värriöjoki representing younger ultramafic magmatism in the ELAD. However, profound conclusions on the magmatic evolution cannot be made on the basis of major and trace element geochemistry only. Isotopic studies would probably help to clarify these issues.

Figure 8.6: Heavily deformed and comprehensively altered ultramafic rock (JHTE-2018-4; x 7495345, y 577821) from the Siurujoki ultramafic complex. Banded weathering surface represents the foliated nature of the rock, with serpentine and metamorphic olivine layers alternating.

8.3 Origin and parental magma composition of the dunitic complexes

In the classic models on the origin of komatiitic dunite bodies, turbulent flow of high volumes of low viscosity komatiitic lava is considered the process that forms large volumes olivine adcumulates (Hill, 1995; Arndt et al., 2008). Based on lithology, it can be assumed that the dunitic bodies of Tulppio and Värriöjoki were formed in this manner. When the significant volume and relatively homogenous geochemical compositions of these dunitic bodies are considered, intrusive origin, suggested for dunitic bodies in some other komatiitic suites (Rosengren et al., 2005), is unlikely for Tulppio and Värriöjoki. It should be noted that empty volumes for such large intrusions is improbable to have been available in the crust, as parental melts (see sections 8.3.1 and 8.3.2) of these complexes are of relatively low viscosity and thus not able to efficiently create space in the crust.

In order to calculate the MgO content of the parental melts of Tulppio and Värriöjoki, methods based on melt-olivine equilibrium were preliminary considered. However, due to strong scatter in data and small amount of analyzed points from individual samples in the pre-existing chemical dataset (Figure 7.41), correlations with whole-rock geochemistry were difficult to perceive. In addition, influence of metamorphism cannot be excluded, as some earlier sampling (Vuollo, 1986) was done on a rather different basis than sampling and analyses required for parental magma calculations.

Therefore, whole-rock geochemistry was used for estimation of parental melts instead. This was done based on utilizing molar TiO_2 in relation to molar MgO and FeO (Makkonen et al., 2017), similar to the parental melt calculations performed for the Jänesselkä complex. For the Värriöjoki ultramafic complex, the calculated forsterite content of the representative olivine cumulate fraction is Fo_{87} (Figure 8.7), whereas the corresponding value for Tulppio ultramafic complex is Fo_{89} (Figure 8.8). These results are supported by mineral chemical analyses (Figure 7.42), where the slightly higher forsterite contents (Fo_{92}) in the olivine from the dunitic core of the Tulppio ultramafic complex can be explained by the effects of magnetite extraction from olivine in dry metamorphic circumstances and the error from the calculations. Parental magmas of Tulppio and Värriöjoki were calculated with the empirical equation (Makkonen et al., 2017) presented in the Section 8.1 and the results are presented below.

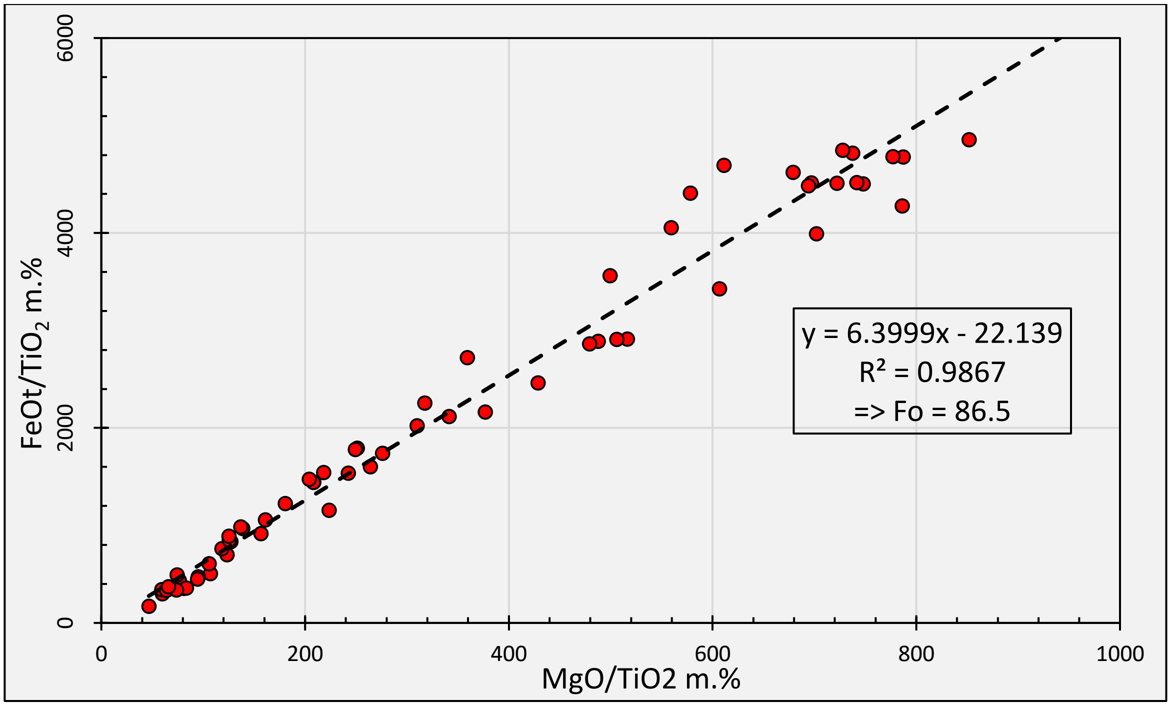

Figure 8.7: Pearce molecular MgO/TiO_2 vs. $FeOt/TiO_2$ plot of the Värriöjoki ultramafic complex. Forsterite content of the cumulus fraction is calculated using the method by Makkonen et al. (2017).

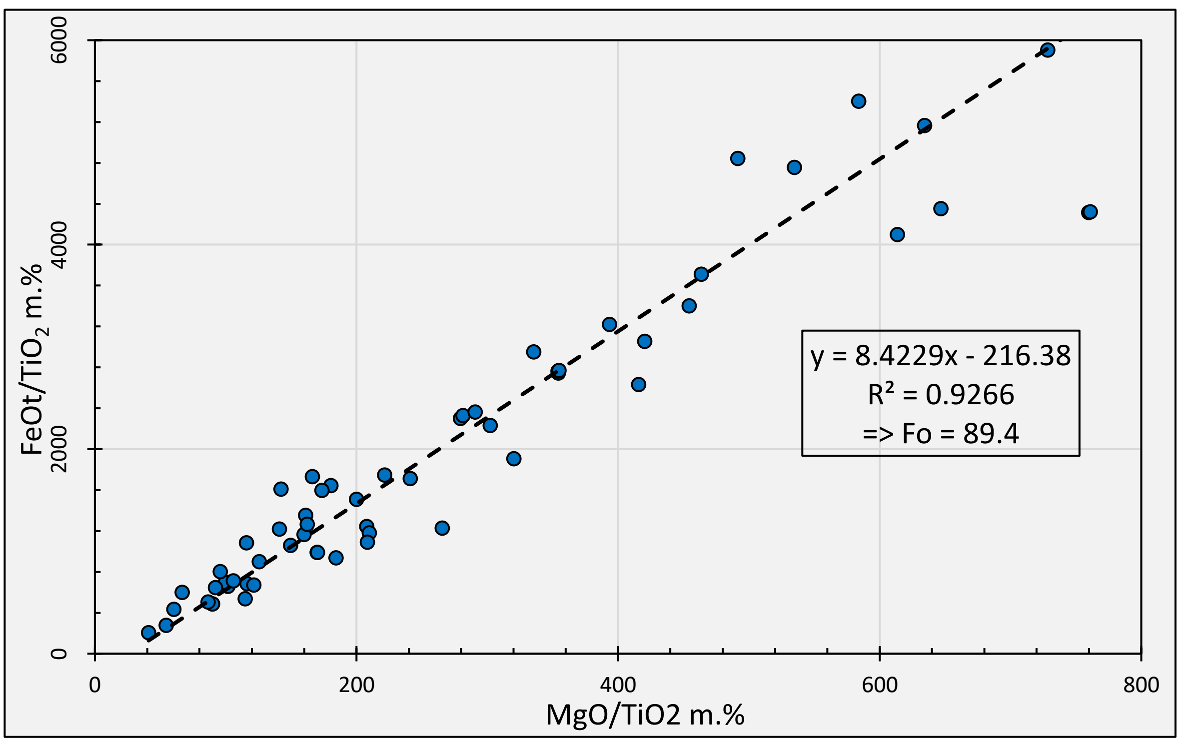

Figure 8.8: Pearce molecular MgO/TiO_2 vs. $FeOt/TiO_2$ plot of the Tulppio ultramafic complex. Forsterite content of the cumulus fraction is calculated using the method by Makkonen et al. (2017).

8.3.1 Tulppio ultramafic complex

The calculation based on cumulus olivine composition as presented in the previous section gives a parental magma composition of komatiitic basalt (~17 wt.% MgO) for Tulppio. The olivine analyses performed in this study (Fo_{92} Figures; 7.36 and 7.37) conform to this. Estimation of the parental melt for Tulppio ultramafic complex by Heikura et al., (2010) suggests a komatiitic melt with 23 wt.% MgO. This and is based on whole-rock geochemistry, where the MgO content of representative cumulus olivine has been estimated from regression line of molar Al_2O_3/MgO vs. TiO_2/MgO. However, clarification on the estimation of FeO content for the parental melt calculation is not presented, which is rather problematic. Therefore, the method implemented by Makkonen et al., (2017) is seen as more robust way for estimating the parental magma composition of the Tulppio ultramafic complex.

Tulppio complex represents a komatiitic adcumulate formed at or near the magmatic vent area (Virransalo, 1985; Halkoaho, 2003; Heikura et al., 2010). Therefore, its role in the formation of the Tulppio metavolcanic belt is important. The komatiitic rocks around Tulppio complex that form most of the TVB were most likely derived from the same parental magmas and early fractionates of these are seen in the Tulppio ultramafic complex. Analogous deformation history of the komatiites of TVB and the surrounding Archean granitoids and the geochemical characteristics, like near chondritic REE patterns, not observed from e.g. komatiitic rocks of the CLGB (Hanski & Huhma, 2005) but typical of Archean komatiites, make an Archean origin for the TVB probable.

8.3.2 Värriöjoki ultramafic complex

According to calculation methods earlier, Värriöjoki had a high-MgO basaltic parental magma with ~12 wt.% MgO. Previous estimates of the parental magma of the Värriöjoki ultramafic complex suggest a picritic (Peltoniemi, 1984) or komatiitic (19 wt.% MgO; Vuollo, 1986) compositions. The former is based on comparison to picrites in eastern Finland (Hanski, 1980), the latter was calculated based on the highest analyzed olivine forsterite content, with no clarification on whether the olivine is magmatic or metamorphic. Therefore, calculations based on olivine may provide ambiguous values, as possible recrystallization may lead to heavily modified MgO contents of the olivine (Nozaka, 2010). This is usually seen as higher forsterite content in metamorphic olivine as a result of metamorphic olivine being produced from magnesian serpentine. Magnetite formed during the serpentinization stays stable in prograde metamorphic conditions and thus there is no significant source of Fe left to the newly formed metamorphic olivine (Zhang, 1981). Based on previous studies and the results of this thesis, determination of the parental magma composition for Värriöjoki complex is seen rather difficult, and thus the MgO content of the parental melt of Värriöjoki is considered to have had the composition of a high-MgO basalt that may have been related to a komatiitic system (komatiitic basalt).

The differences in the major element geochemistry and slight differences in calculated parental melt compositions of Tulppio and Värriöjoki support the idea of the Värriöjoki ultramafic complex representing younger magmatism than that of TVB, which is considered as Archean (Juopperi & Vaasjoki, 2001). High-Mg basaltic parental melt calculated for Värriöjoki corresponds to those of many other ultramafic suites of northern and eastern Finland, with average parental melt with ~11 wt.% MgO calculated for the 2.44 Ga layered intrusions (Alapieti et al., 1990). In addition, recently published Sm-Nd isotope compositions from Värriöjoki comply with the possibility of the Värriöjoki complex correlating with the 2.45 Ga ultramafic rocks in the Koulumaoiva intrusion (Huhma et al., 2018).

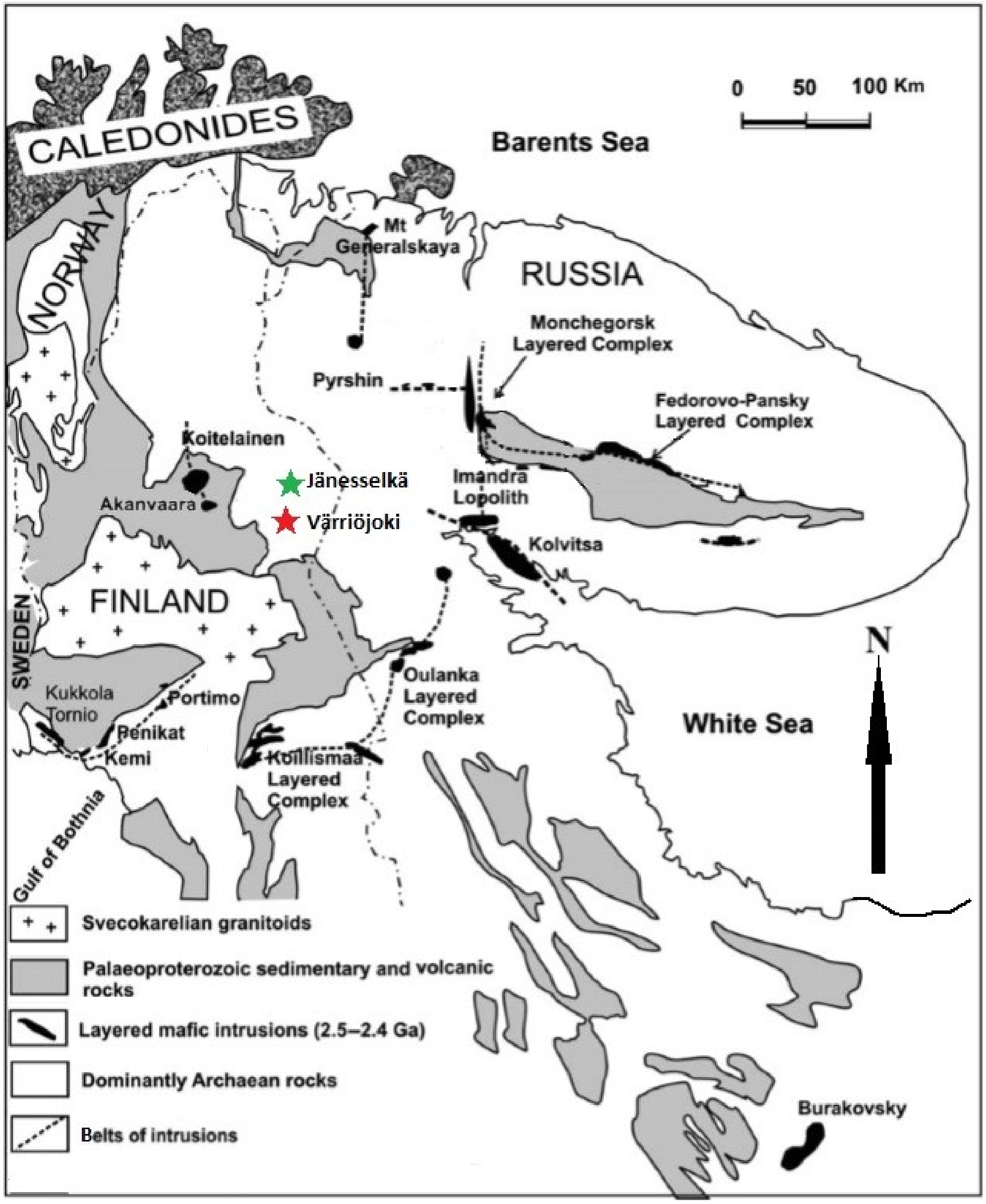

Figure 8.9: The location of Jänesselkä and Värriöjoki and Paleoproterozoic mafic-ultramafic layered intrusions on a generalized geological map of the northeastern part of the Fennoscandian shield. Modified after Bayanova et al. (2009).

Paleoproterozoic mafic-ultramafic layered intrusions are widespread in the Fennoscandian shield (Bayanova et al., 2009) (Figure 8.9). In addition to the Finnish layered intrusions, such as Kemi (Alapieti & Huhtelin, 2005), Penikat (Alapieti & Lahtinen, 1986), and Näränkävaara (Alapieti et al., 1990) and their related cumulates, mafic to ultramafic rock associations related to 2.45 Ga magmatism are abundant within the Archean bedrock of Karelian province. From these, trace element contents for 2.45 Ga mafic layered intrusions and associated komatiitic rocks have been analyzed from the Vetreny belt, south of the White Sea, Russia (Puchtel et al., 1997). Their geochemical characteristics include a major crustal component and high Sm/Ti and U/Nb, which also observed in some of the Finnish 2.45 Ga mafic-ultramafic rocks (Lauri et al., 2012). When the trace element contents of the komatiitic cumulates, komatiitic basalts, and mafic volcanic rocks of the Vetreny belt are compared to those of the Leppäselkä block of the Värriöjoki ultramafic complex (Törmänen et al., 2007), marked similarities are observed, including the aforementioned high Sm/Ti and U/Nb (Figure 8.10). These features are also seen in the Jänesselkä mafic-ultramafic complex, from which one sample (HMHO-2017-20.1) has trace element data available. These correlations support the model of a single plume, underlying the 2.5 Ga Fennoscandian shield (Puchtel et al., 1997; Lahtinen et al., 2008), as the source for extensive ultramafic magmatism, with crustal anatexis and fractionation of mafic-ultramafic magmas as main mechanisms for formation of mafic and felsic intrusive rocks. In this model, ultramafic complexes of great volume, like Värriöjoki and Näränkävaara represent major pathways for mantle derived-magmas that formed smaller mafic-ultramafic intrusions like Jänesselkä, Akanvaara and Koulumaoiva.

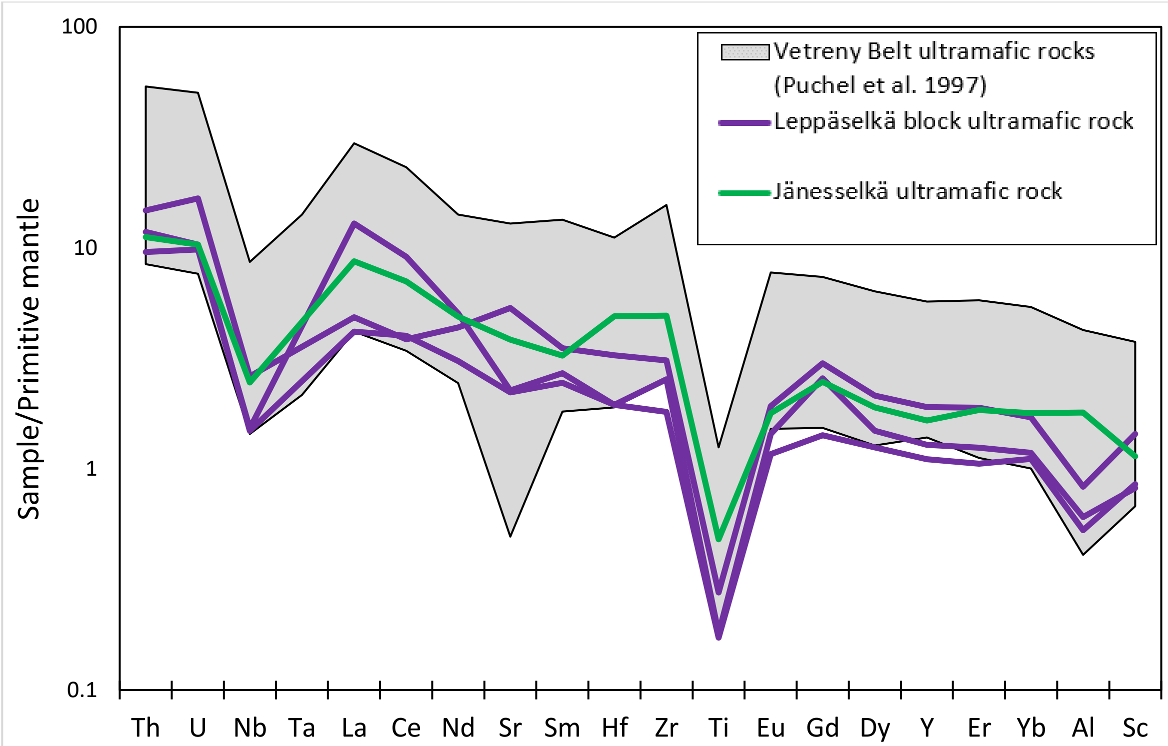

Figure 8.10: Primitive mantle-normalized (Hoffmann, 1988) spider plot from representative samples from diamond drill hole 4711/06/R25 from Leppäselkä block, Värriöjoki ultramafic complex (Törmänen et al., 2007) and sample HMHO-2017-20.1 from the Jänesselkä mafic-ultramafic complex. Grey area represents the variation in trace element content from 20 komatiitic basalt samples from Vetreny belt, NW Russia (data from: Puchtel et al., 1997).

9 CONCLUDING REMARKS

The Jänesselkä mafic-ultramafic complex shows lithological and geochemical characteristics atypical for komatiitic rocks forming the Tulppio metavolcanic belt. Its origin may significantly differ from previous interpretations of its origin as a cumulate body of Archean komatiitic magmatism. Based on the estimates of this study, the parental magma for Jänesselkä mafic-ultramafic complex was basaltic, the present rock types mostly representing the most MgO-rich cumulate fraction of an intrusion. Together with recently performed age determinations (Tepsell, 2018), the trace element content of Jänesselkä suggests it being a product of early phases of magmatism related to the Paleoproterozoic rifting of the Fennoscandian shield (Lahtinen et al., 2008). The geochemical features also suggest about possibly similar primary magma with the one estimated for the Värriöjoki ultramafic complex.

Ultramafic complexes of Tulppio and Värriöjoki represent cumulate bodies formed from high volumes of turbulently flowing magmas with composition of high-Mg basalt. The two complexes cannot be considered as comagmatic as their geochemical compositions and features observed in the field differ significantly. Recent Sm-Nd studies (Huhma et al., 2018) from the Värriöjoki ultramafic rocks and estimations of its parental magma conform to 2.4–2.5 Ga magmatism forming the major layered intrusions and some of the greenstone belts in the northern Fennoscandian shield. This is supported by the trace element patterns, characteristic of other early Paleoproterozoic mafic-ultramafic complexes in the northern Fennoscandian shield. Therefore, a possibility of the ultramafic complex of Värriöjoki (and Jänesselkä) being products of mantle-plume derived magmatism starting at 2.45 Ga is notable. However, to deepen the understanding about their origin, isotope studies are seen as a necessity.

Based on parental melt calculations, the Tulppio ultramafic complex was formed from a magma with more than 15 wt.% MgO. Therefore, it is the only complex studied in this thesis with possibly komatiitic parental magma. This is also supported by the geochemical characteristics of the Tulppio ultramafic rocks, with features typical of Archean komatiites. Owing to the poor level of exposure, heavy alteration, and the lack of isotope data, accurate interpretations of the formation of the Tulppio ultramafic complex are pending.

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